THE UNIVERSITY OF ALBERTA

THE INFLUENCE OF UPPER-LEVEL WINDS AND TEMPERATURES ON THE ORGANIZATION OF HAIL PATTERNS IN CENTRAL ALBERTA

by

(C) William C. Thompson

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA

SPRING, 1970

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Influence of Upper-Level Winds and Temperatures on the Organization of Hail Patterns in Central Alberta", submitted by William C. Thompson in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Hail periods in Central Alberta for the years 1957 through 1968 are studied. The hail periods are divided into three samples based on the degree of organization of the pattern of hail reports volunteered by farmers to the Alberta Hail Studies Project.

The hail periods in which the hail reports were well organized into swath hail patterns (swath hail periods) are shown to have a greater frequency of southwesterly 500-mb winds, stronger 400-mb wind speeds and warmer 700-mb temperatures than the least organized scattered hail periods but the differences are insufficient for each parameter alone to clearly distinguish the two samples. When the 400-mb wind speed and the 700-mb temperature are considered together, the swath and scattered hail periods are better distinguished.

The wind directions are nearly constant with height from 700 mb to 200 mb for all three samples. Some evidence is presented that the vertical wind shear component along the hailswath for the long swath hail periods reverses direction about 50 mb above the surface.

Most of the hailswaths are first detected in generation areas along the foothills. Nearly all of the hailswaths are first detected between 1100 and 2000 MST. Longer hailswaths tend to originate prior to 1700 MST. The hailswaths are directed about 25° clockwise from the 500-mb wind.

Swath hail periods in which long hailswaths are produced subject much more area to damage than shorter swath hail periods

or the hail periods with less organized hail patterns. It is roughly estimated that 50 percent of the average annual area subjected to hail damage is subjected during a small number of long swath hail periods.

The findings here are in general agreement with the findings of hail research carried out in Colorado, Illinois and South Dakota.

ACKNOWLEDGEMENTS

I am sincerely grateful to a number of people without whose assistance and advice this thesis could not have been completed.

The data required for this study were made available by the Alberta Hail Studies section of the Research Council of Alberta. In particular, I wish to express thanks to Mr. F. Bergwall for his comments on the operation and limitations of the radiosonde tracking equipment, to Mr. L. Wojtiw and Mr. J. Renick for the Fortran subroutine to convert land locations to x-y coordinates, and of course to Dr. P.W. Summers, whose counsel stimulated many of the approaches for this study.

I wish to express gratitude to my departmental supervisor, Professor R.W. Longley for suggesting changes and additions, to Dr. K.D. Hage for his comments on the handling of statistical problems, and to Dr. E.R. Reinelt for his advice relating to computer programming.

This research was carried out while I was employed by the Meteorological Branch of the Department of Transport.

Mrs. J. McGregor is commended for her efficiency in typing this manuscript.

Finally, special thanks go to my wife, Marie, whose encouragement and enduring support contributed much to the accomplishment of this research.

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CHAPTER I

INTRODUCTION

Research projects have been established in many parts of the world to study the hail-producing thunderstorm. Much of the research has been oriented to thunderstorm dynamics and cloud physics. Study of the actual cause of concern, the hail, has generally been in the form of climatological investigations of point hailfall and studies of a small number of destructive hailstorms which are not characteristic of hailstorms in general.

Theoretical thunderstorm models such as those of Newton and Newton (1959), Browning (1964) or more recently Takeda (1969) consider environmental winds and temperatures as important parameters in their development. There is a requirement to examine the influence of these parameters on the hailstorm - hailfall relationship.

The Alberta Hail Studies (ALHAS) Project has been in operation over the fourteen year period, 1956 to 1969, inclusive, and has a sufficient number of hail reports from its large cooperative network of volunteer observers to make such a study possible.

Recent Research

At least three studies have discussed the climatology of hail in Alberta. Powell (1961) investigated the storm tracks and observed that those in the southern part of the province tended to be oriented northwest to southeast whereas those in the north-central part tended to be oriented west to east or southwest to northeast. Paul (1967) and Summers and Paul (1970), whose studies were of point

hailfall, observed geographically preferred areas for hailfall in central Alberta and also noted that a hailfall maximum occurs early in the afternoon near the foothills and moves slowly eastward as the afternoon progresses.

Studies of the synoptic conditions of hail and no-hail days in Alberta have been made primarily with a view to forecasting potential hail-days. Longley and Thompson (1965) established a comprehensive forecast procedure which employed 700-mb temperature, low-level moisture, instability, upper-level winds and vorticity. To minimize the preparation time of hail forecasts, Sly (1965) introduced an instability index, the Slydex. Resumes of hail seasons by various authors[1] of the Edmonton Weather Office have dealt with several aspects of the synoptic conditions.

Carte (1963) noted that hailswaths in Alberta were oriented to the right of the wind direction in the lower and middle troposphere. Using radar data from two Alberta hailstorms, Chisholm (1967) suggested that the hailswaths were produced by a series of cells each of which developed on the right flank of the thunderstorm complex and progressed to the left across the storm path.

The role of upper winds in thunderstorm development has been examined by many authors without reaching a consistent conclusion. For instance, Proppe (1965) found no significant difference between maximum wind distributions on severe hail-days and on "milder thunderstorm days." His results further showed that wind shear may in fact

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[1] Contained in Toronto, Dept. of Transport, Meteorological Branch, Technical Circular Series Nos. 236, 276, 317, 341, 388, 443, 493, 565, 611, 674, 688, 699.

hinder most hailstorm development. These results are similar to those expressed earlier by Ratner (1961). Yet, Dessens (1960), Schleusener (1962), Das (1962), Frisby (1964) and Modahl (1969) generally found that strong wind shear and strong winds aloft are important in the development of severe hailstorms though not all agree on the layer in which the shear should be greatest.

The Alberta Hail Studies Project

All hailstorm data were obtained from the archives of the Alberta Hail Studies Project.

The Project has been in operation since 1956 and depends on voluntary reporters, predominantly farmers, for its observations. The boundaries of the Project Area, as shown in Fig. 1.1, have remained unchanged since 1958. In 1957 the encompassed area was slightly smaller.

The observations have been submitted on a hail report card similar to that shown in Fig. 1.2. Previous to 1962 these cards were unsolicited, that is, they were mailed in by the farmers or the data were telephoned to the Project's field headquarters at Canadian Forces Base Penhold. In 1962 and later years hail reports were also solicited for many of the major hailstorms. These were obtained by Project personnel through personal and telephone interviews of residents of the areas affected by these hailstorms. Hailstorms from which numerous hail reports were solicited for the purpose of providing a detailed picture of the hailfall are referred to as surveyed hailstorms.

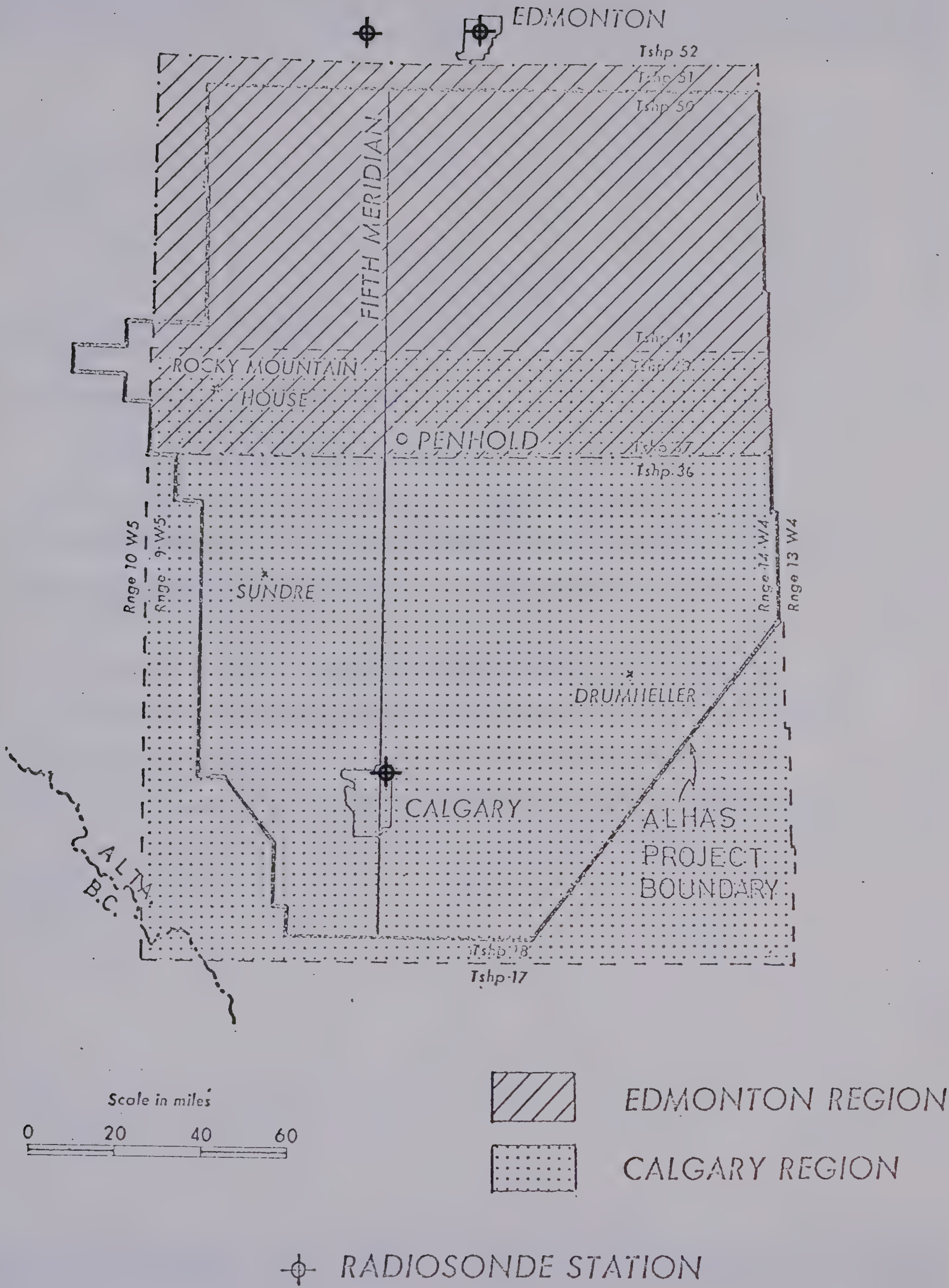


Fig. 1.1 The Alberta Hail Studies Project Area and the Edmonton and Calgary regions.

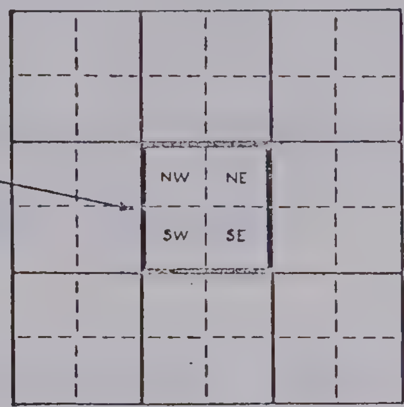
L | P | I | M | C | |

(1) Date of Storm: 1968

(2) Location of observed hail occurrence:

..... 1/4, S....., T....., R....., W of .....

Please indicate with X exact spot on section map



(3) Hail began at ....AM or at ....PM ;

Hail lasted for .... minutes.

(4) During this time: it never stopped hailing ☐ ;

OR there were ☐ bursts of hail;

OR there were an unknown number of bursts ☐ .

(5) Size of largest hail: shot ☐ ; pea ☐ ; grape ☐ ; walnut ☐ ; golfball ☐ ; larger ☐ .

Size of most common hail: shot ☐ ; pea ☐ ; grape ☐ ; walnut ☐ ; golfball ☐ ; larger ☐ .

(6) Average spacing of hailstones on the ground at end of storm was .... inches.

OR if ground covered, depth of hail was .... inches.

(7) Hail began: before rain ☐ ; at same time ☐ ; after rain began ☐ ; OR no rain ☐ .

(8) Largest hail fell: at beginning ☐ ; in middle ☐ ; towards the end ☐ ; throughout storm ☐ .

(9) Was any hail soft or slushy: yes ☐ ; no ☐ : if yes what was the estimated largest size ....

(10) Were any hailstones of irregular shape? none ☐ ; a few ☐ ; about half ☐ ; OR most ☐ .

(11) Indicate on section grid other nearby properties on which you know it hailed.

(12) How much rain fell during the storm .... inches.

(13) Remarks:

Name .... Address ....

If you need more cards, check here ☐ Phone .... Exchange ....

Fig. 1.2 Sample hail report card.

There have been minor changes in the card format since its inception (see McBride, 1964) but the data pertinent to this study have remained unaffected by these changes. A history of the Project and a thorough description of the data collection are given by Paul (1967).

The data from the hail report cards have been coded and are stored on magnetic tape to facilitate computer processing.

Objectives

The objectives of this research are three-fold, namely:

1) to examine the influence of the upper level wind directions, wind speeds and temperatures on the organization of the pattern of hail reports.

2) to investigate the relationship between the organization of the pattern of hail reports and the damage in the agricultural community of the Project Area.

3) to identify some characteristics of the more destructive hailstorms.

CHAPTER II

PREPARATION OF DATA

Four stages were required to prepare the data for analysis. These were: preparation of the hail-day plots, abstraction of the radiosonde data, selection of the hail periods from the hail-day plots, and grouping the hail periods into hail patterns. The first two stages were computer-processed.

The Hail-day Plots

The twelve-year period 1957 to 1968, inclusive, was selected for study. The data of 1956 were excluded because the Project area was much smaller that year. Those of 1969 were also excluded because they were not coded until well after this study was initiated.

The University of Alberta's IBM 360-67 computer and its CALCOMP plotter attachment were used to plot charts of the location of hail reports for each day in which fifteen or more were received. There were 314 of these hail-day plots. Examples are shown in Figs. 2.1 to 2.3.

The computer programming was simplified by plotting all reports within the area enclosed by the northern edge of township 51, the eastern edge of range 14, the southern edge of township 18 and the western edge of range 9 (see Fig. 1.1). The additional hail reports contributed from the areas appended on the western side and the southeast corner of the Project Area are negligible due to the low population densities there. The hail reports from townships 18 and 51 were plotted to permit analysis of the hailstorms within the Project Area but near the south and north boundaries.

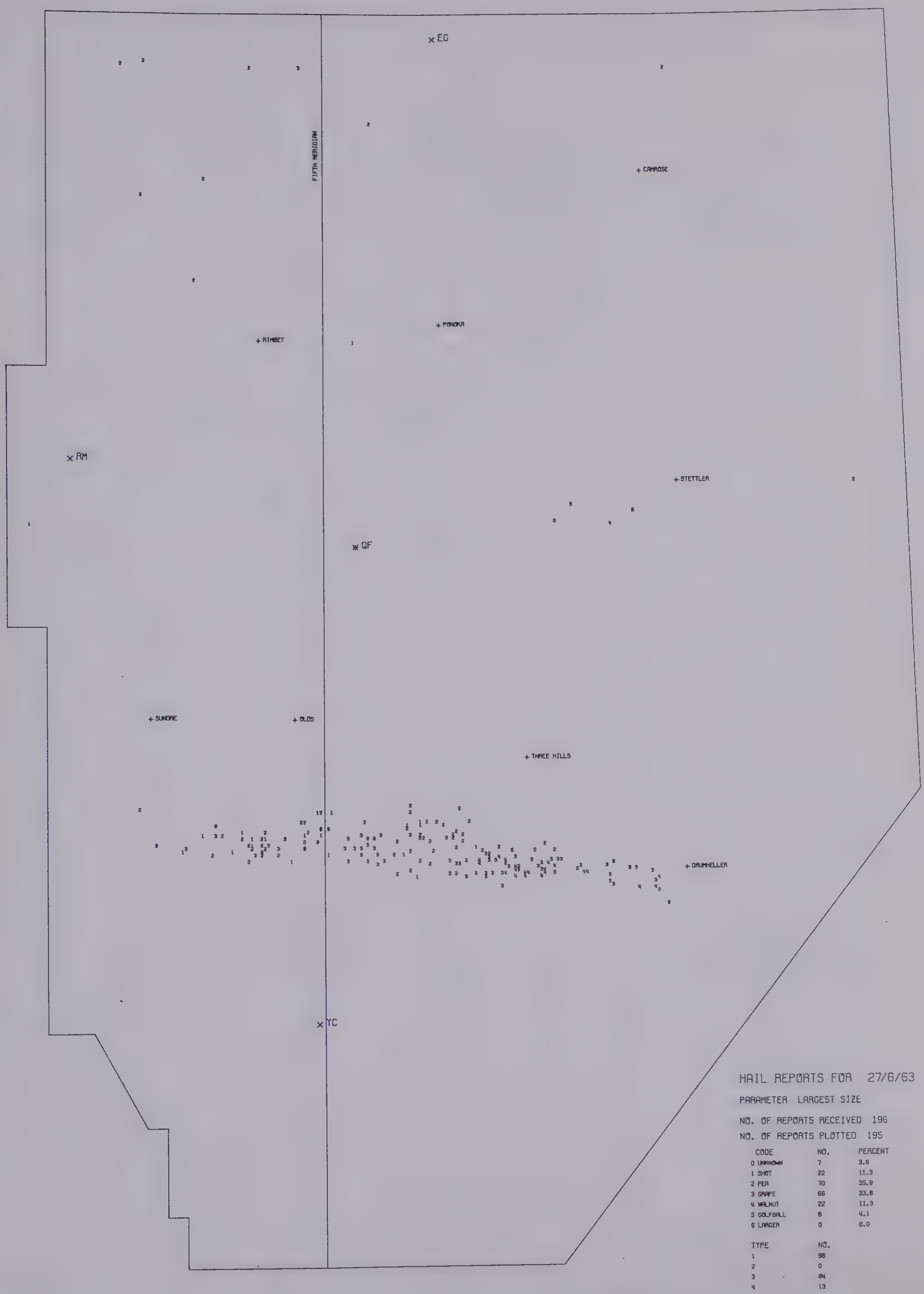


Fig. 2.1 Hail-day plot showing a swath hail pattern in the Calgary Region.

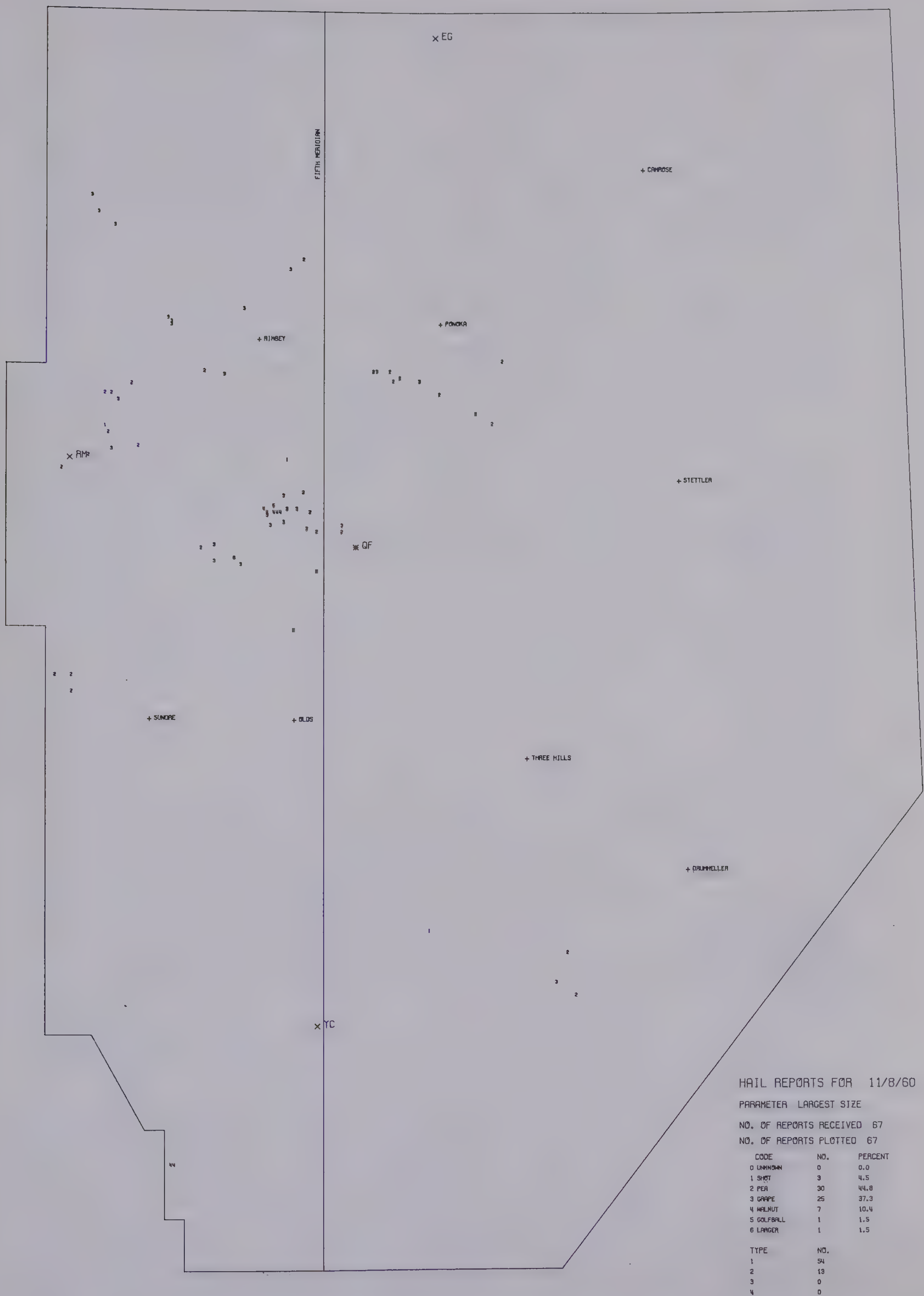


Fig. 2.2 Hail-day plot showing a scattered-swath hail pattern in the Edmonton Region.

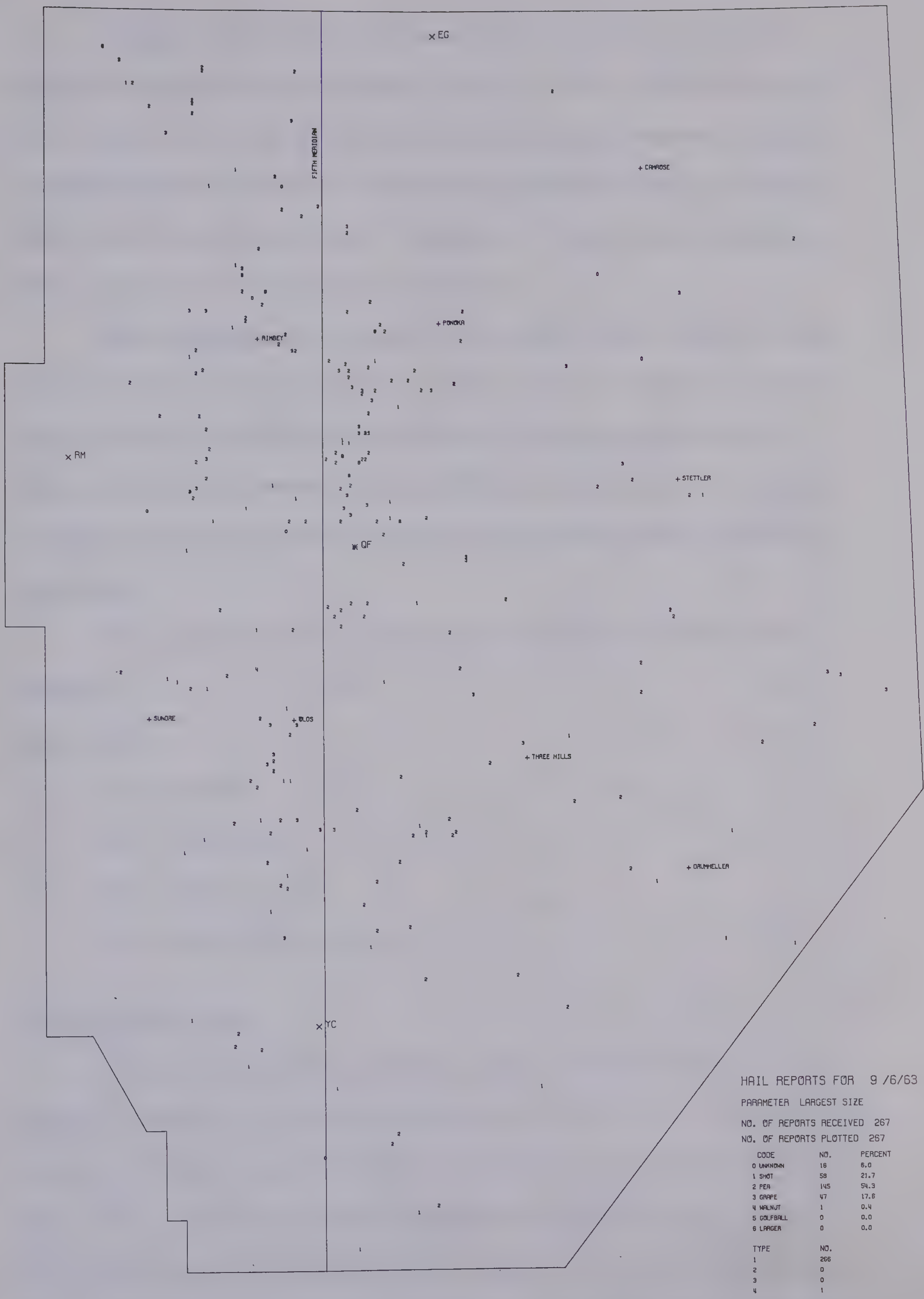


Fig. 2.3 Hail-day plot showing a scattered hail pattern in each Region.

Largest size rather than modal size was selected as the plotted parameter for two reasons. First, it was requested by the hail report cards back to 1957 whereas modal size was not. Second, the distribution of largest sizes from a hailstorm covers a wider range than that of modal size. Therefore, largest size provides a better opportunity to distinguish storms.

Some statistics are given in the lower right corner of each hail-day plot. These include the number of hail reports received and the number of hail reports plotted. The difference arises because some reports come from outside the boundaries. The number of reports plotted is used as a total for computing the remaining statistics.

The type of report refers to the method by which it was received.

These were:

1) by mail
2) by telephone
3) by car survey
4) by telephone survey

The Radiosonde Data

Edmonton Industrial Airport, about 15 miles north of the northern boundary of the Project Area, was the site of a Meteorological Service of Canada upper-air observing station up to and including 1965. This station was moved approximately 20 miles west to near Stony Plain prior to the 1966 hail season. Therefore, complete upper-air data are available throughout the period from the Edmonton area.

In addition the Meteorological Service of Canada operated an upper-air station at the Calgary Airport for the Alberta Hail Studies Project during the months June, July and August from 1962 to 1968, inclusive. Most of the observations in 1963 were made at 0500 MST. Consequently there are few 1700 MST ascents for that year.

The locations of the three upper-air observation sites are shown in Fig. 1.1.

The Selection of Hail Regions and Hail Periods

The hail-day plots were examined with the objective of minimizing the spatial and temporal differences between the hail reports and the upper air data.

The Project Area was divided into two regions, an Edmonton and a Calgary region as shown in Fig. 1.1. An overlap of four townships permitted sufficient flexibility that many of the hailstorms in the central section could be represented by one set of upper air data rather than the two that would have been required had no overlap been allowed.

Two time periods were considered for each region. These were a morning period from 2300 to 1059 MST and an afternoon period from 1100 to 2259 MST. They were chosen such that the environmental conditions of the region were represented by the 0500 and 1700 MST upper-air observations, respectively.

The selection of time periods for analysis involved a two-stage processing of each hail-day plot. In the first stage, that region was selected which contained the greater number of plotted

hail reports. If it contained less than fifteen unsolicited hail reports[1], the hail-day plot was rejected from further processing. If it contained more than 15 the data of the region were considered for the second stage. If the remaining Project Area outside this region contained 15 or more plotted reports the data of the second region were also considered for the second stage.

In the second stage the times of the hail reports were examined. If 80 percent or more of the times given by the hail reports for the region fell in one time period and an upper-air observation was available, the data were selected for analysis. Exceptions were made where it was obvious that two unrelated hail-producing systems produced fifteen or more hail reports in each period of a region. Those time periods selected for analysis were termed <u>hail periods</u>.

The foregoing is clearly an attempt to ensure that the data of the hail periods were represented as close in time and space as the upper-air observation network would allow. A total of 223 hail periods were selected of which only seven were morning time periods.

<u>Classification of Hail Periods</u>

A hailswath was defined as an elongated cluster of at least

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[1] A provision had to be made for surveyed hail-days because it was likely that more hail reports would have been volunteered had the survey not taken place. The procedure established by Paul (1967) was adopted. He found on the average that 15 percent of the solicited reports would have been received had a survey not been carried out. This figure probably varies somewhat from storm to storm due to the thoroughness of the survey and its proximity in time to the storm occurrence. All references to the number of unsolicited hail reports in this paper will mean the number of unsolicited plus 15 percent of the solicited reports.

ten hail reports which were temporally coherent. The maximum separation allowed between two adjacent hail reports was six miles.

The spatial distribution of the hail reports of each hail period was classified as of one of three hail patterns on the basis of the following criteria:

1) Hailswath or swath pattern
    a) one or more hailswaths were evident, and
    b) the number of reports in hailswaths constituted more than two-thirds of the total.
2) Scattered-swath pattern
    a) one or more hailswaths were evident, and
    b) the number of reports in hailswaths constituted two-thirds or less of the total.
3) Scattered pattern

    No hailswath was evident.

For convenience hail periods in which the hail pattern was swath, scattered-swath and scattered are referred to as swath hail periods, scattered-swath hail periods and scattered hail periods, respectively. An example of each is shown in Figs. 2.1, 2.2, and 2.3.

Temporal coherence was checked with the assistance of a computer-prepared table which gave the means of the times of all hail reports per township after appropriate allowances had been made for erroneous and rounded times (see Williams and Douglas, 1963).

Table 2.1 gives the number of hail periods found with each hail pattern for both regions.

Table 2.1 Frequency of Swath, Scattered-Swath and Scattered Hail Periods for each Region

Hail Pattern	Edmonton Region Morning	Edmonton Region Afternoon	Edmonton Region Total	Calgary Region Morning	Calgary Region Afternoon	Calgary Region Total	Total
Swath	4	50	54	0	36	36	90
Scattered swath	1	33	34	1	32	33	67
Scattered	1	36	37	0	29	29	66
Total							223

CHAPTER III

THE INFLUENCE OF WIND

Both the wind direction and speed are generally considered to play roles in the movement and development of hailstorms. Thunderstorms are steered by the upper winds. As a result, upper level wind directions are useful in predicting areas likely to be subjected to hail. Some theoretical thunderstorm models require that the winds veer with height. Other research has shown that destructive hailstorms are frequently associated with strong upper level winds.

The wind directions and speeds at various levels from the surface to 200 mb of the hail periods with each hail pattern are examined after first discussing a bias introduced to the wind data due to the inability of the older-style radiosonde tracking equipment to measure strong winds.

Instrument Failures

The Calgary Radiosonde station used the Metox, and Edmonton, up to and including 1965, used the SCR658 RDF tracking equipment. Both instruments were unable to record wind data when the balloon was less than fifteen degrees above the horizon, a situation that often occurred with strong winds. As a result there are reports of missing winds, particularly above the 400-mb level, which, if ignored, give a bias to the samples.

A newer-style GMD RDF tracking instrument was installed at the Edmonton station when it was relocated at Stony Plain in 1966. The result has been that the wind data have been complete for nearly all ascents since that date.

Wind Direction

In examining the wind direction, the objectives were threefold, namely: to compare distributions of 500-mb wind directions associated with the hail patterns, to relate the orientation of the hailswaths to the upper wind directions and to compare the directional wind shears associated with the hail patterns.

500-Mb Wind Direction

Figs. 3.1 and 3.2 show the percentage frequency distributions of 500-mb wind directions for the Edmonton and Calgary regions, respectively, for the swath, scattered-swath and scattered hail periods. Also shown in each figure for comparison is a climatological distribution composed of all 1700 MST July[1] soundings. The median values shown were computed from an origin at 80 degrees from true north. The figures show that:

1) For each region, there is a clockwise progression of the 500-mb median wind direction from the swath to the scattered hail periods. For example, the median wind veers from 242 degrees for the swath hail periods to 250 degrees for the scattered hail periods in the Edmonton region, and from 255 to 273 degrees, respectively, in the Calgary region.

2) For the hail periods with each pattern, there is a clockwise progression of the 500-mb median wind direction from the

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[1] These computations were prepared from all 1700 MST July soundings taken at Edmonton during the period 1961 to 1968, inclusive, and at Calgary during the period 1962 to 1968, inclusive. Additional climatological data for the months of June, July and August are given in Fig. 1 of Appendix A.

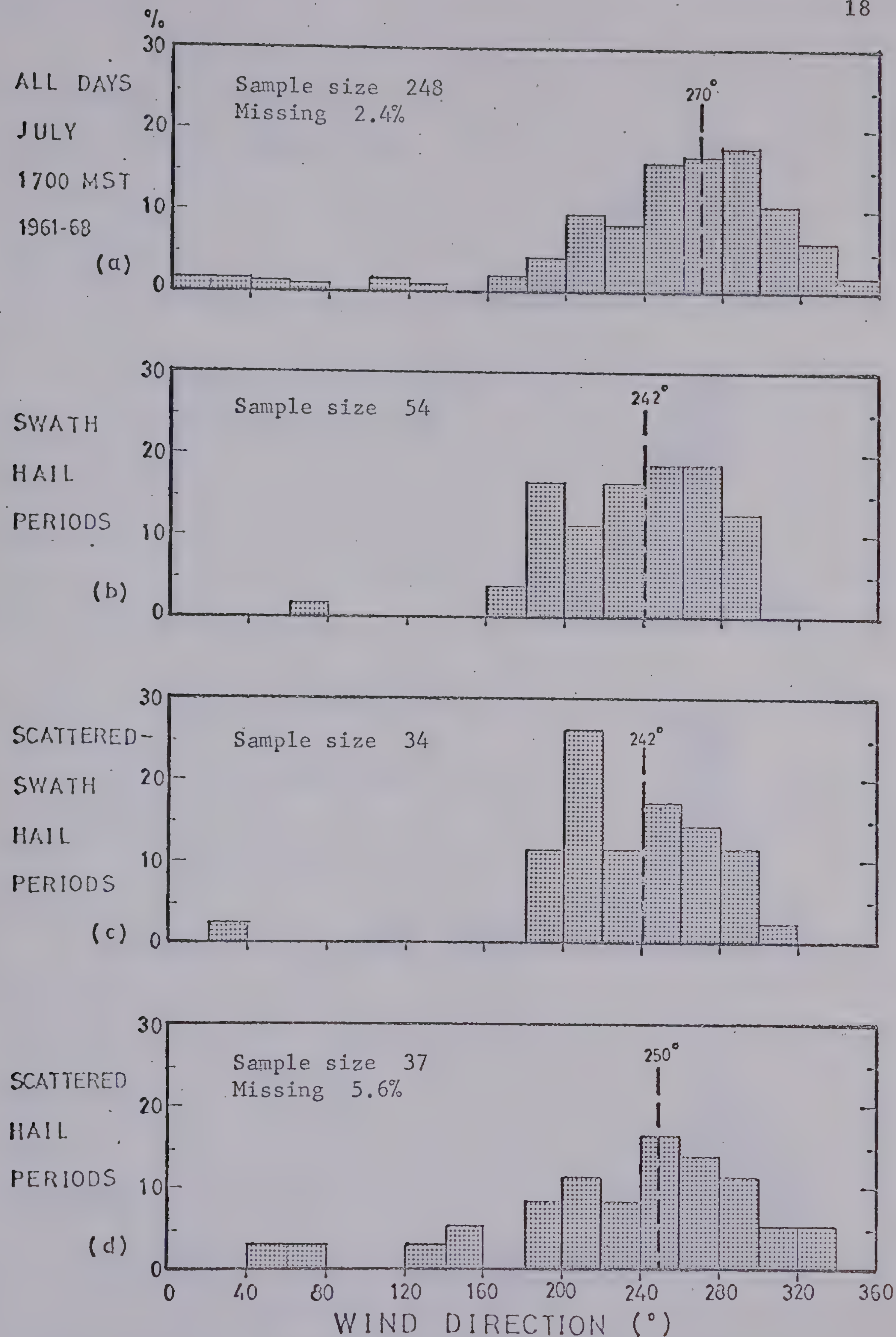

Fig.3.1 Percentage frequency distributions of 500-mb wind directions at Edmonton.(a) shows the distribution for all 1700 MST July soundings and (b),(c), and (d) show the distributions for the hail periods with each hail pattern.Dashed vertical lines denote median wind direction computed from an origin at 80°.

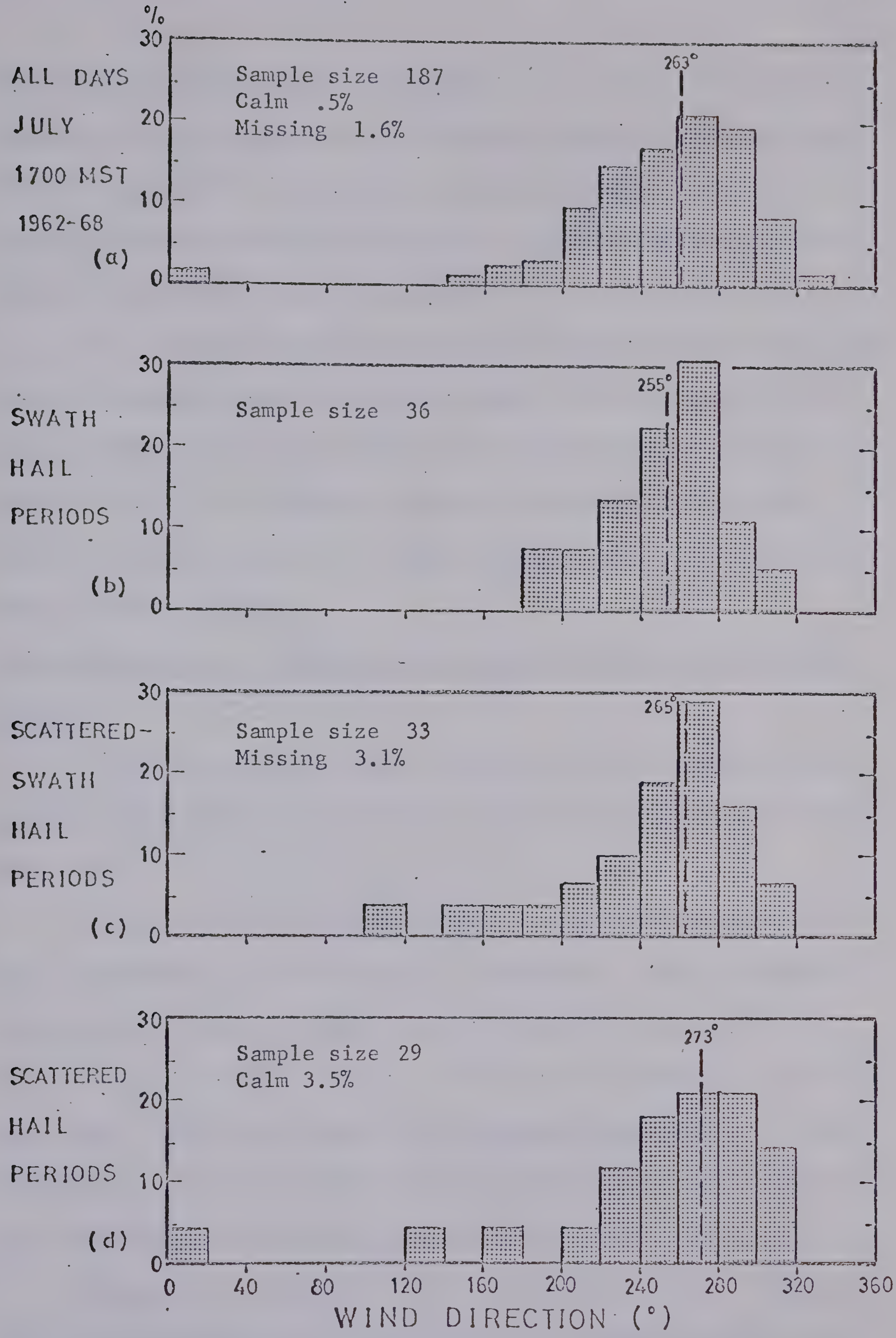

Fig. 3.2 Percentage frequency distributions of 500-mb wind directions at Calgary.(a) shows the distribution for all 1700 MST July soundings and (b),(c),and (d) show the distributions for the hail periods with each hail pattern.Dashed vertical lines denote median wind direction computed from an origin at 80°.

Edmonton to Calgary region. For example, the median wind direction for the swath hail periods in the Edmonton region is 242° and in the Calgary region 255°. In addition, the distributions tend to be narrower and more peaked in the Calgary region indicating less variability in the 500-mb wind directions.

3) The wind distributions for the hail periods in the Calgary region resemble those for all days in July. Therefore, the 500-mb wind direction is of little value for differentiating hail-days from no-hail days. In the Edmonton region the distinction is greater. Winds on hail-days tend to be southwesterly whereas those on no-hail days tend to be westerly.

The Wind Direction - Hailswath Direction Relationship in Swath Hail Periods

In this section the swath hail periods are studied with the objective of relating the swath directions and the upper-level wind directions.

A hailswath axis was determined for each hailswath by visually estimating a line of best fit through it. The direction in which the hail was laid down along the swath axis was labelled in degrees from true north using the convention for designating wind directions. This was defined as the hailswath direction. In cases where more than one hailswath occurred, the mean of their directions was considered as the hailswath direction for those hail periods.

In order to comprehend better the changes in wind direction with height relative to the swath axes, the hailswath direction was considered the independent variable and the wind directions at each level

were considered with reference to it. For each swath hail period, wind directions at the surface, 900 mb,[2] each 50 mb level from 900 to 700 mb and each 100 mb level from 700 to 200 mb were subtracted from the swath direction to obtain the respective wind deviations. A positive value indicated a counterclockwise wind deviation, a negative value indicated a clockwise wind deviation. Fig. 3.3 illustrates how the wind deviation was obtained for one level.

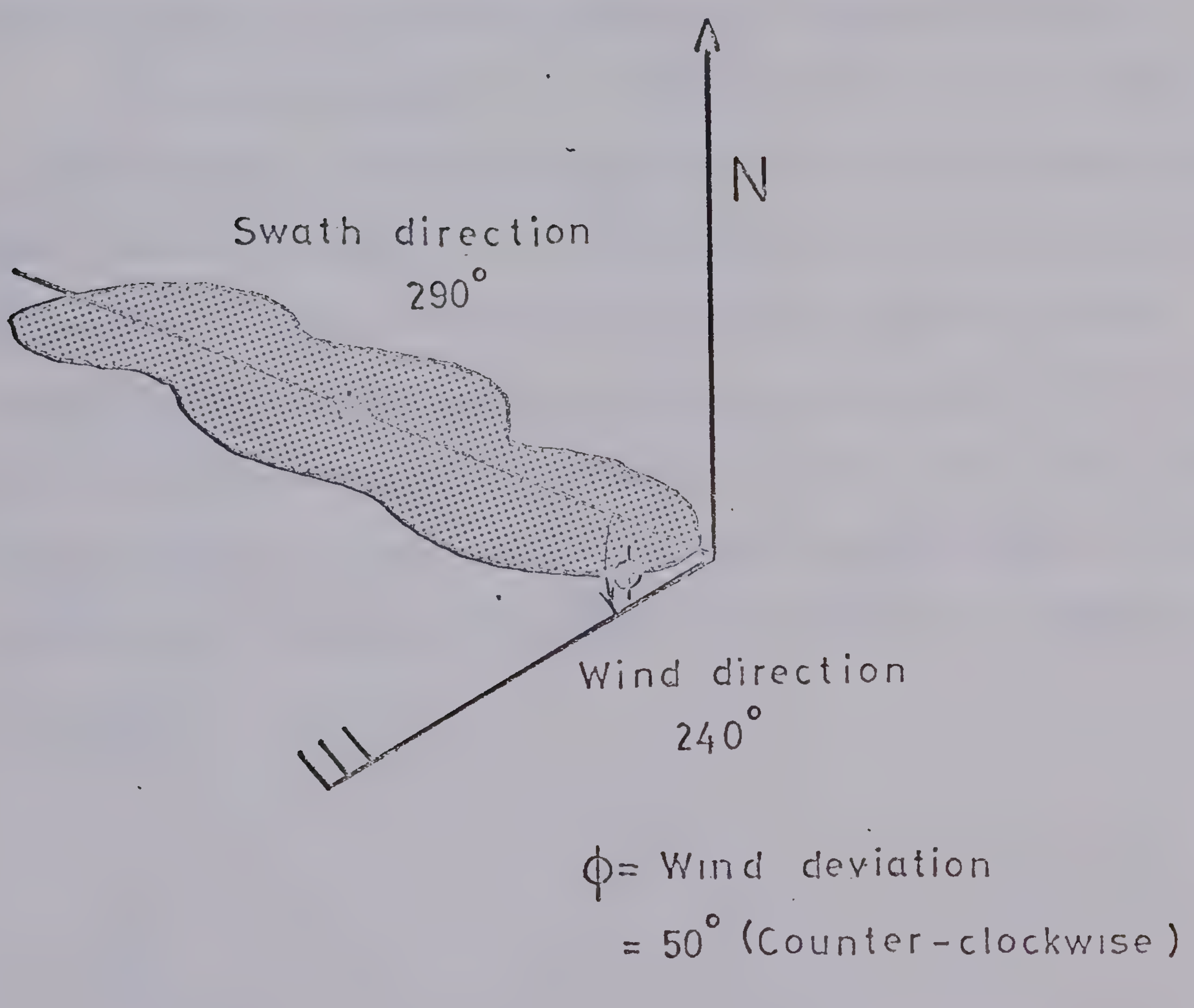

Fig. 3.3 Example illustrating procedure for determining wind deviation at one level

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2 The surface and 900-mb level at Calgary are assumed coincident throughout this study.

The frequencies of wind deviations at each level are shown in Tables 3.1 and 3.2. The mean of the hailswath directions for all swath hail periods was 263° in the Edmonton region and 273° in the Calgary region.

From the surface to 750 mb the winds relative to the swath axis are variable, indicating that no consistent relationship between the wind direction and the swath direction exists in this layer. From 700 mb to 200 mb most wind deviations are concentrated in the intervals from 0 to 40° counterclockwise to the swath axis showing that the winds are of constant direction throughout the layer.

The median deviations are shown in Table 3.3. This Table is intended to be used to determine the swath direction given the wind direction. Therefore, the wind direction is considered as the independent variable. With missing wind data excluded from the computation of the medians, it is seen that the median swath direction is 20 to 30° clockwise from the wind direction at most levels from 700 mb to 200 mb. For practical purposes the best estimate would be given by a clockwise swath deviation of 25° from the 500-mb wind direction.

Table 3.1 Frequency Distributions of Surface and Upper-Level Wind Directions Relative to Swath Direction.

Region: Edmonton

Pattern: Swath

No. of cases: 54

MBS	161–180	141–160	121–140	101–120	81–100	61–80	41–60	21–40	1–20	0–19	20–39	40–59	60–79	80–99	100–119	120–139	140–159	160–179	CALM	MISSING
	◁COUNTER-CLOCKWISE ←									← CLOCKWISE →										
200					2	1	5	14	13			1								18
300		1		1	1	2	8	15	14	2	1									9
400			1		1	1	8	18	18	2	1	1						1		2
500	1				1	2	8	18	15	8	1									
600			1		1	2	10	12	19	7	2									
700		1	1	1	1	2	6	16	12	11	2	1								
		1		1	3	2	6	11	15	5	6	1	1			1	1			
800	1			2	4	4	6	12	4	7	6	3	1		2	1	1			
		3	4	1	3	3	5	4	1	6	6	3	2	4	4		3	2		
900	4		2	2	3	4	1	2	3	2	7	5	6	5	2	1	3	2		
	2	2	3	2	4	3	3		2	2	5	11	4	5	4		2			

DEVIATION FROM SWATH AXIS (°)

Table 3.2 Frequency Distributions of Surface and Upper-Level Wind Directions Relative to Swath Direction.

Region: Calgary

Pattern: Swath

No. of cases: 36

MBS	COUNTER-CLOCKWISE									CLOCKWISE									CALM	MISSING
	161–180	141–160	121–140	101–120	81–100	61–80	41–60	21–40	1–20	0–19	20–39	40–59	60–79	80–99	100–119	120–139	140–159	160–179		
200				1		1	4	6	4	1										19
300							9	9	4	1	2									11
400				1		1	5	16	7	1	1									4
500					1		5	15	13	1	1									
600							9	11	10	5	1									
700					1	3	7	14	5	4	1	1								
			1	1	7	1	4	10	3	5	1		1				1		1	
800	2	3	1	4	5		3	2	2	5	4	2		2					1	
	3	3	3	2	2	1	2		3	2	2	1	2	2	3	1	2	2		
900	5	2	3	1	1	4		2	1	2	1	3	3	3	2		1	2		

DEVIATION FROM SWATH AXIS (°)

Table 3.3 Median Deviation of Swath Direction from the Wind Direction

Level (mb)	Clockwise Deviation (°)	
	Edmonton Region	Calgary Region
200	26	32
300	28	33
400	24	29
500	24	23
600	19	24
700	22	28

Changes in Wind Direction with Height

Changes in wind direction with height for each hail period were studied by using the 500-mb wind as a reference for wind directions at levels above and below. The procedure is identical to that of the previous section except that deviations are from the 500-mb wind direction instead of the swath direction.

The distribution of deviations for each level with each hail pattern are shown in Tables 3.4 to 3.9 of Appendix B for both regions. For reference purposes the median 500-mb wind direction associated with each hail pattern may be obtained from the appropriate histogram of Figs. 3.1 and 3.2.

In general terms it may be stated that more directional shear is indicated in the 700 to 200 mb layer for the scattered and

scattered-swath hail periods than for the swath hail periods. It is likely that this is a result of the lighter winds associated with these patterns as will be shown in the next section. From 700 mb to the surface the distributions broaden with all hail patterns. As a result no consistent wind direction changes may be identified with any hail pattern in this layer.

Wind Speed

Wind speeds are considered in two sections. The first examines the mean wind speed profiles associated with the three hail patterns, and the second examines the wind components along the swath axis for the swath hail periods.

Mean Wind Speed Profiles

Mean wind speed profiles are presented in Figs. 3.4 and 3.5 for the Edmonton and Calgary regions, respectively. In Fig. 3.4 mean values above 400 mb are for the period 1966 to 1968, inclusive, when the GMD RDF tracking equipment was in use. There were no missing wind data among the samples for that period.

In Fig. 3.5 the profiles were continued upward till the missing data comprised twelve percent or more of the sample. The actual numbers of missing reports may be obtained from the right-most column of the appropriate Table of Tables 3.4 to 3.9 of Appendix B.

Both figures show similar mean wind speeds associated with all hail patterns from the surface to about 700 mb. Above 700 mb the mean wind speeds for the swath periods are stronger than those with the scattered-swath and scattered hail periods, and the means of all 1700 MST observations. The variability, as expressed by the

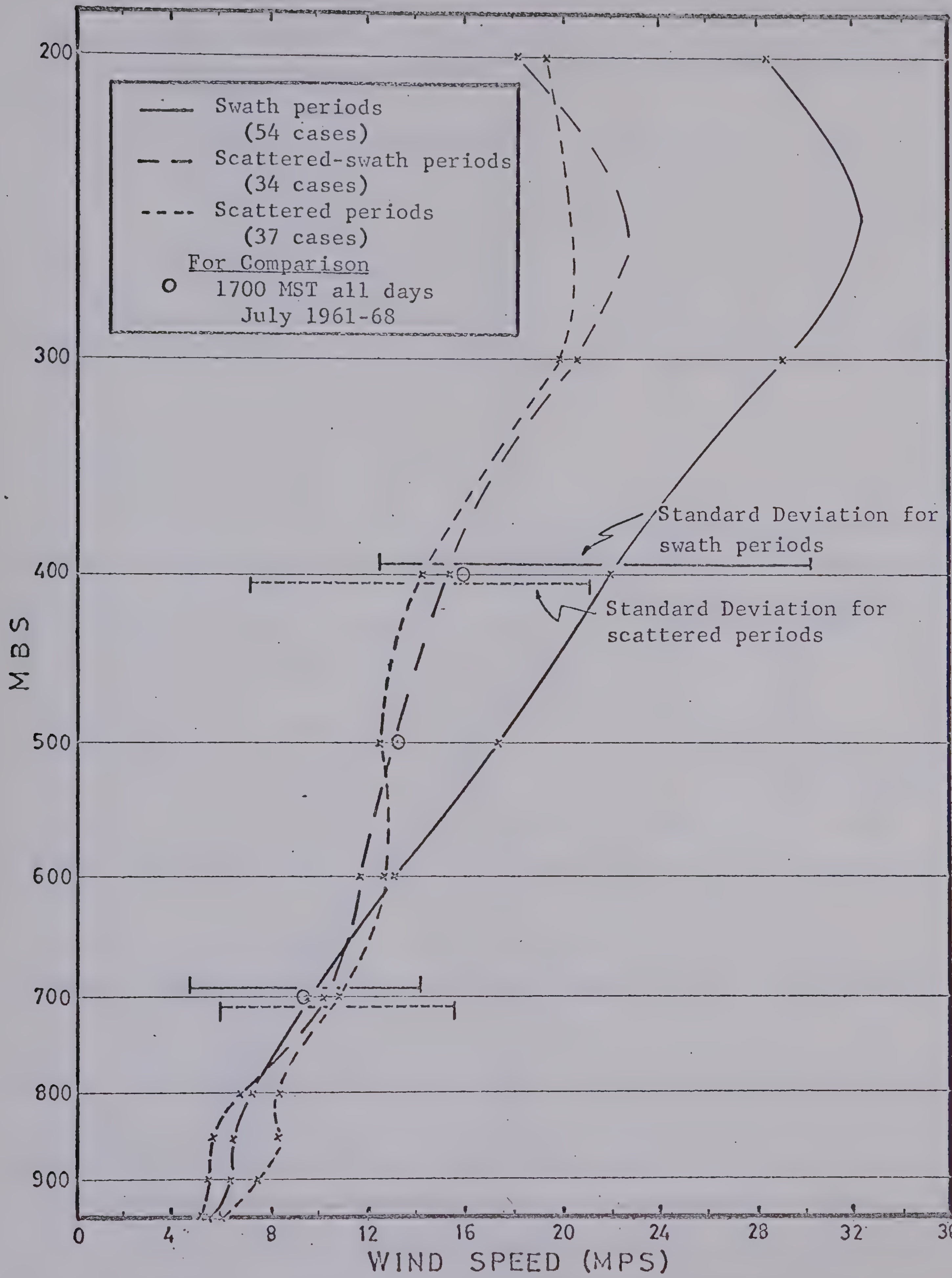


Fig.3.4 Mean wind speed profiles for the Edmonton region. The values shown at 300 mb and 200 mb were calculated from 13 swath, 12 scattered-swath and 12 scattered hail periods for the years 1966 through 1968 when the GMD RDF tracking equipment was in operation.

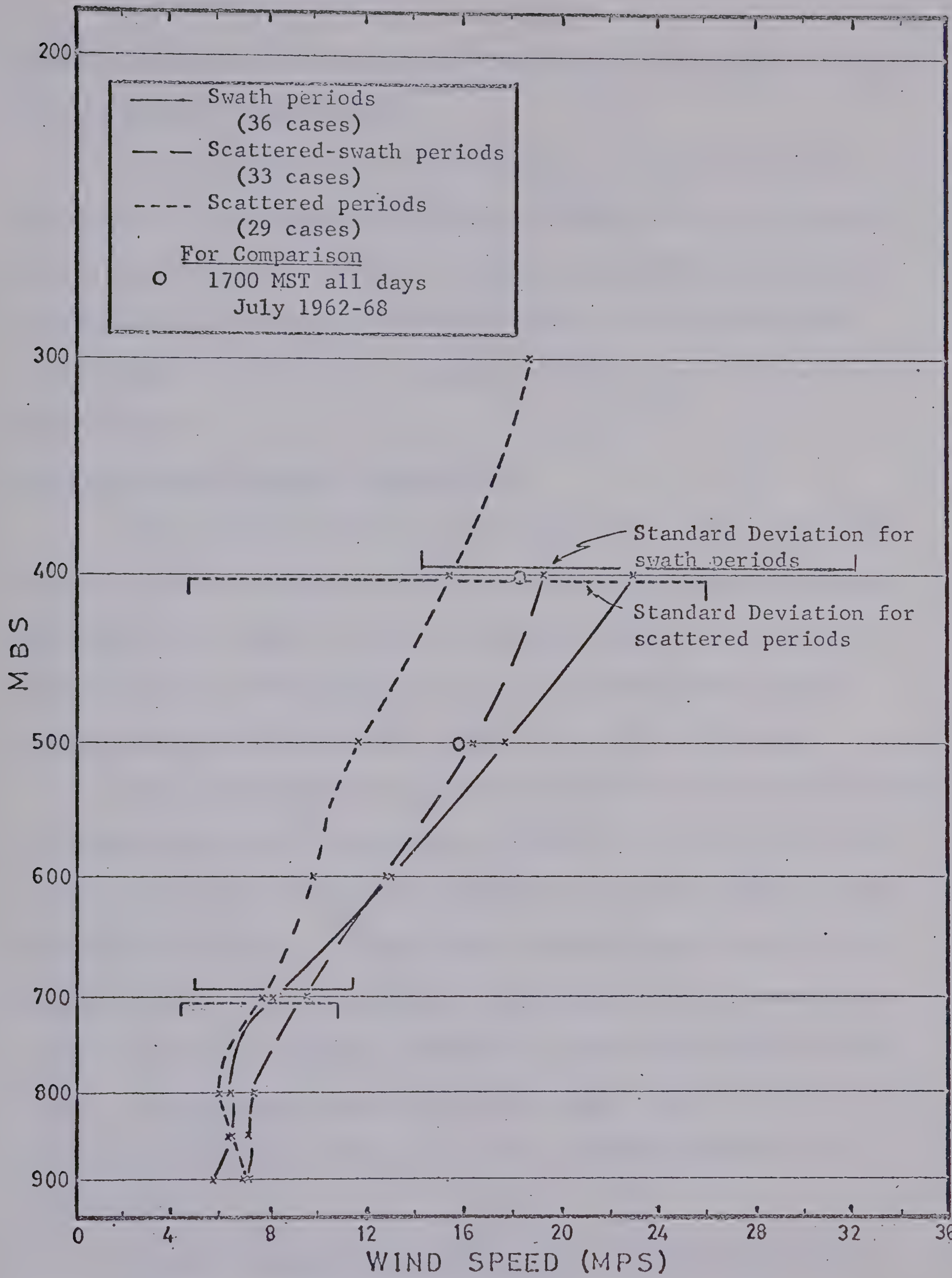


Fig.3.5 Mean wind speed profiles for the Calgary region.

standard deviation, is also greater for the swath hail periods than for the scattered hail periods.

It must therefore be concluded that hail patterns in the presence of strong upper-level winds are likely to be well organized in the form of swaths. However, the great variability of the wind distributions associated with swath patterns also indicates that strong winds aloft are not a necessary condition for the formation of hailswaths.

Wind Components Parallel to Swath Axes

The swath hail periods in each region were subdivided on the basis of the mean swath length per hail period into three divisions. Hail periods in which the mean of the swath lengths was less than forty miles were termed short, forty to sixty miles were termed medium-length and greater than sixty miles were termed long.

The wind component parallel to the mean of the swath directions was tabulated at each level from the surface to 300 mb for each hail period. The median values for each swath length division are shown in Figs. 3.6 and 3.7. In cases where wind data were missing at the 400 and 300-mb levels, the median was determined in the conventional manner assuming the missing components to have been present but very large. In the Calgary region where the sample sizes were small and the number of missing reports was large, the 300-mb medians were not calculated.

In both regions, the low-level wind components associated with the long swaths decrease from the surface to a minimum about 50 mbs above the surface and then increase steadily upwards to 300 mb.

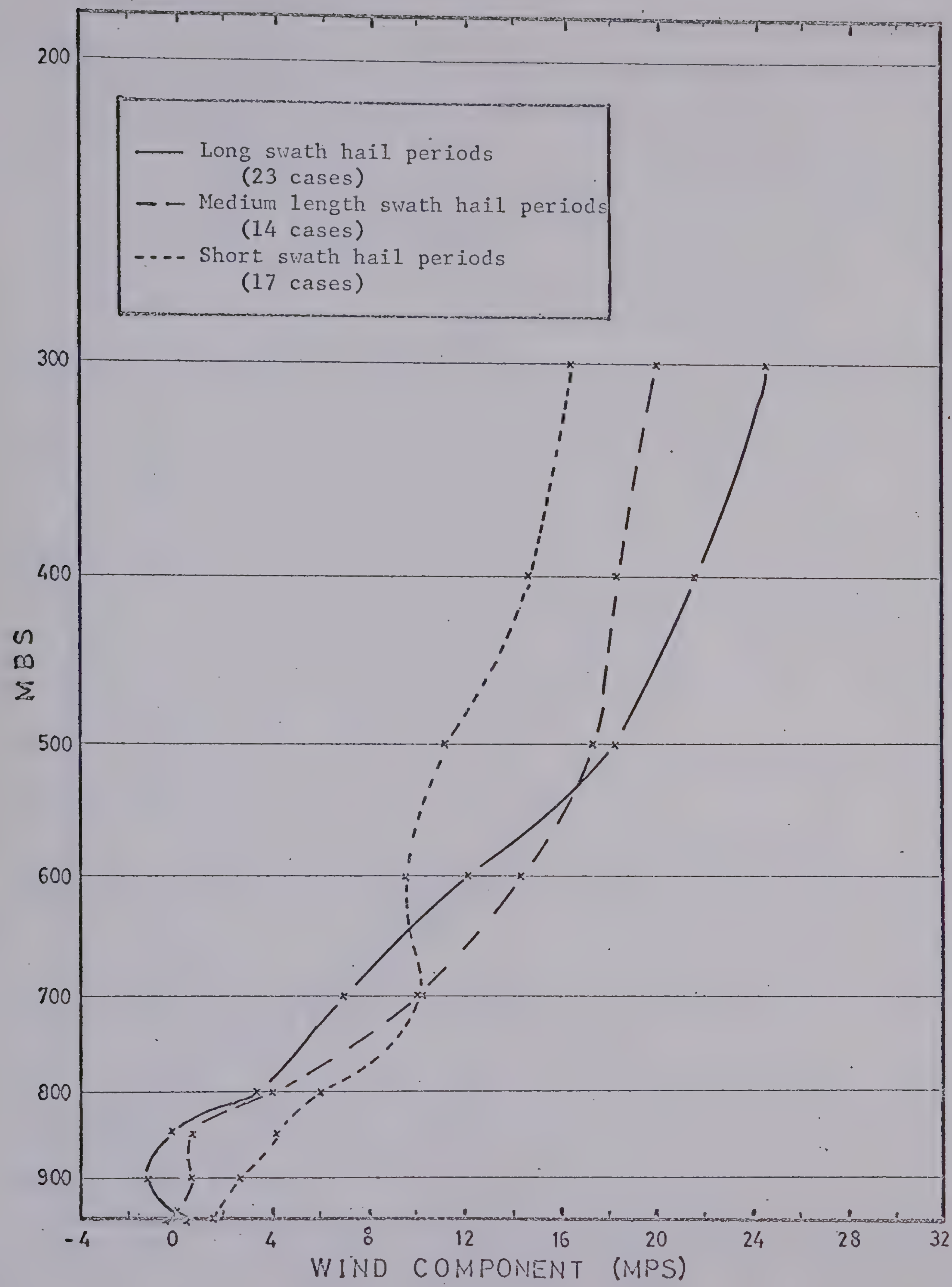


Fig.3.6 Median wind components parallel to the swath direction in the Edmonton region.

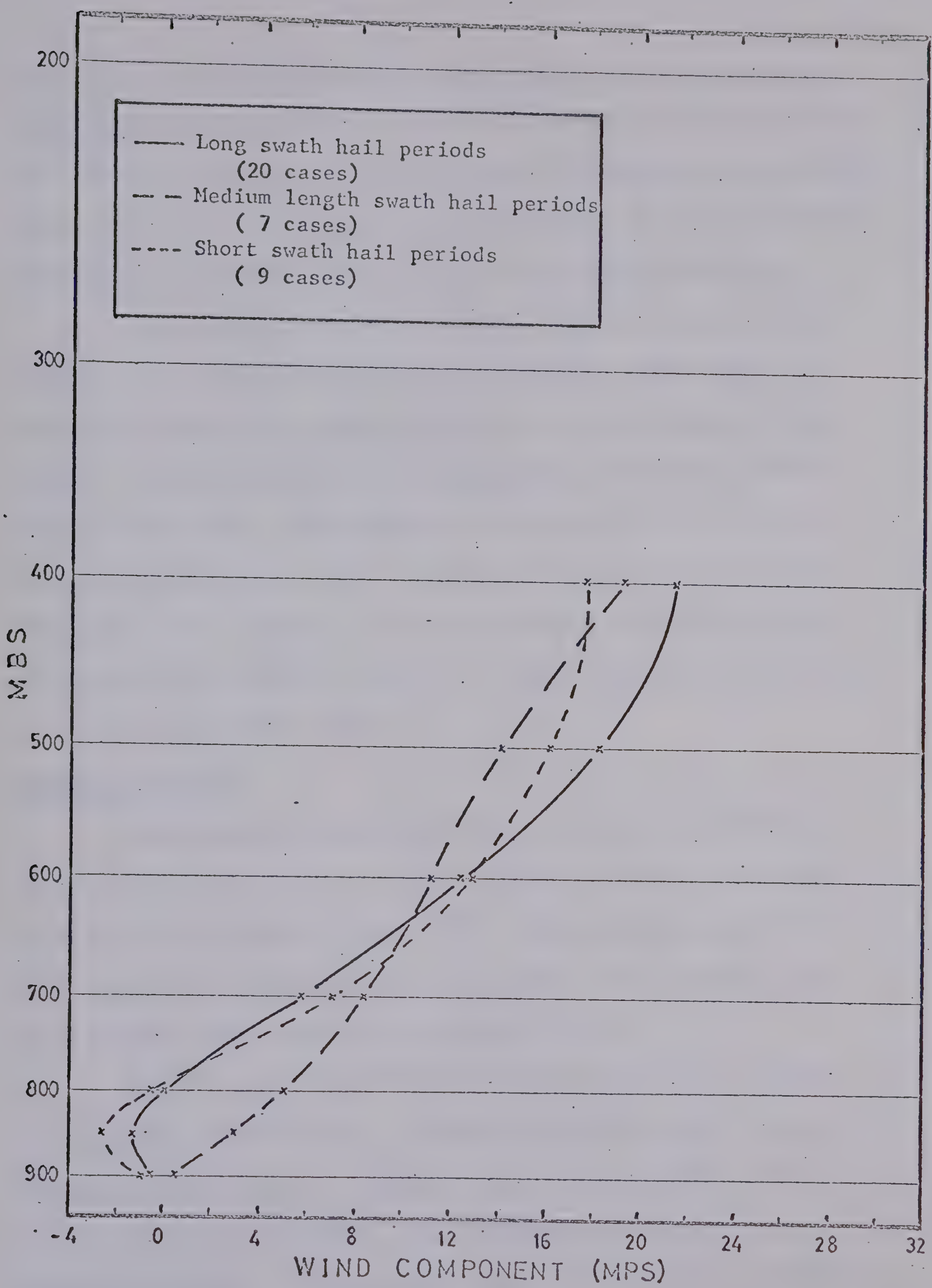


Fig.3.7 Median wind components parallel to the swath direction in the Calgary region.

The low-level wind components with each of the medium length and short swath samples, however, show little similarity between regions. This may be in part due to the smallness of the samples in the Calgary region but it could also be due to the fact that the low-level winds are light and probably reflect the local prevailing directions.

In the levels from 500 mb upward, where the wind field is assumed to be uniform throughout the region, the median wind components are larger for long swaths than for medium length or short swaths. If it is assumed that the deviations of the short swaths from the upper level wind directions are the same as those for the long swaths, then the larger components are due to stronger winds. This infers that stronger vertical wind shear in the 700 mb to 400 mb layer not only tends to produce swath hail patterns but also tends to produce longer hail swaths.

Summary of Results

The foregoing results show that swath producing hailstorms in the ALHAS Project Area are nearly always associated with 500-mb wind directions between 180 and 300^{o}. Wind directions associated with the scattered patterns are, on the whole, more westerly and more variable than those with the swath patterns.

The direction of the hailswath axis is about 25^{o} clockwise to the 500-mb wind direction. Because 500-mb winds under hailswath-producing conditions are frequently between 240 and 280^{o} in the southern part of the Project Area, hailswath orientations there tend to be WNW-ESE. In the northern part of the Project Area where

the 500-mb winds tend to be more southwesterly, swath orientations are frequently WSW-ENE.

There is a direct relationship between the upper-level wind speed and the degree of organization of the hail pattern. Well defined hailswaths are associated with strong upper-level winds whereas loosely organized hailswaths and scattered hail reports are associated with lighter upper winds. Furthermore, the length of the hailswath is influenced by the strength of the upper winds. Hailswaths tend to be longer when the upper winds are stronger.

CHAPTER IV

THE INFLUENCE OF TEMPERATURE

The most vigorous and long-lived hailstorms in Alberta occur when environmental temperatures are near the mid-summer mean. In colder environments, hailstorms tend to be short-lived and produce predominantly small hail. It is improbable that the ambient vertical temperature structure alone is responsible for these differences. The strength of the upper winds and the degree of instability, which is temperature dependent, likely play more important roles in determining hailstorm intensity.

Temperature Profiles

The mean temperature profiles for the hail periods with each hail pattern are shown in Figs. 4.1 and 4.2 for the Edmonton and Calgary regions, respectively. For comparison mean July 1700 MST temperatures for 1961 to 1968, inclusive, at Edmonton are shown in Fig. 4.1 and the mean 500-mb July 1700 MST temperature for 1962 to 1964, inclusive, at Calgary after Sly (1965) is shown in Fig. 4.2. Mean 1700 MST temperatures for all days are given in Fig. 2 of Appendix A for the months June, July and August at Edmonton.

Also shown for comparison are 500, 700 and 850-mb temperatures for days without hail. These are the means of 1700 MST July soundings randomly selected from days on which no hail reports were received by the ALHAS Project. The sample size at Edmonton was 82 for the period 1957 to 1967, inclusive, and at Calgary was 50 for the period 1962 to 1967, inclusive.

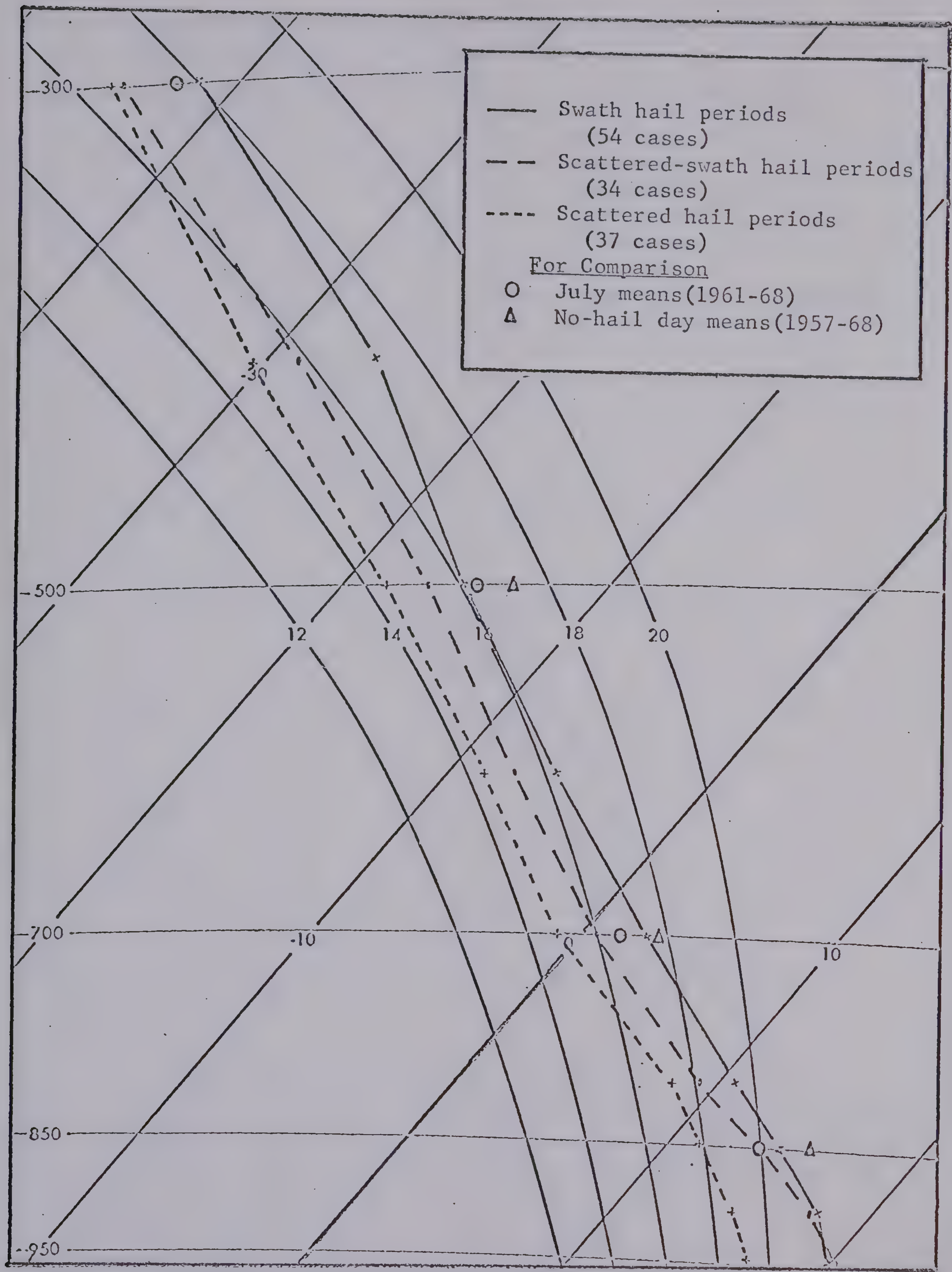


Fig.4.1 Mean temperature profiles for the Edmonton region.

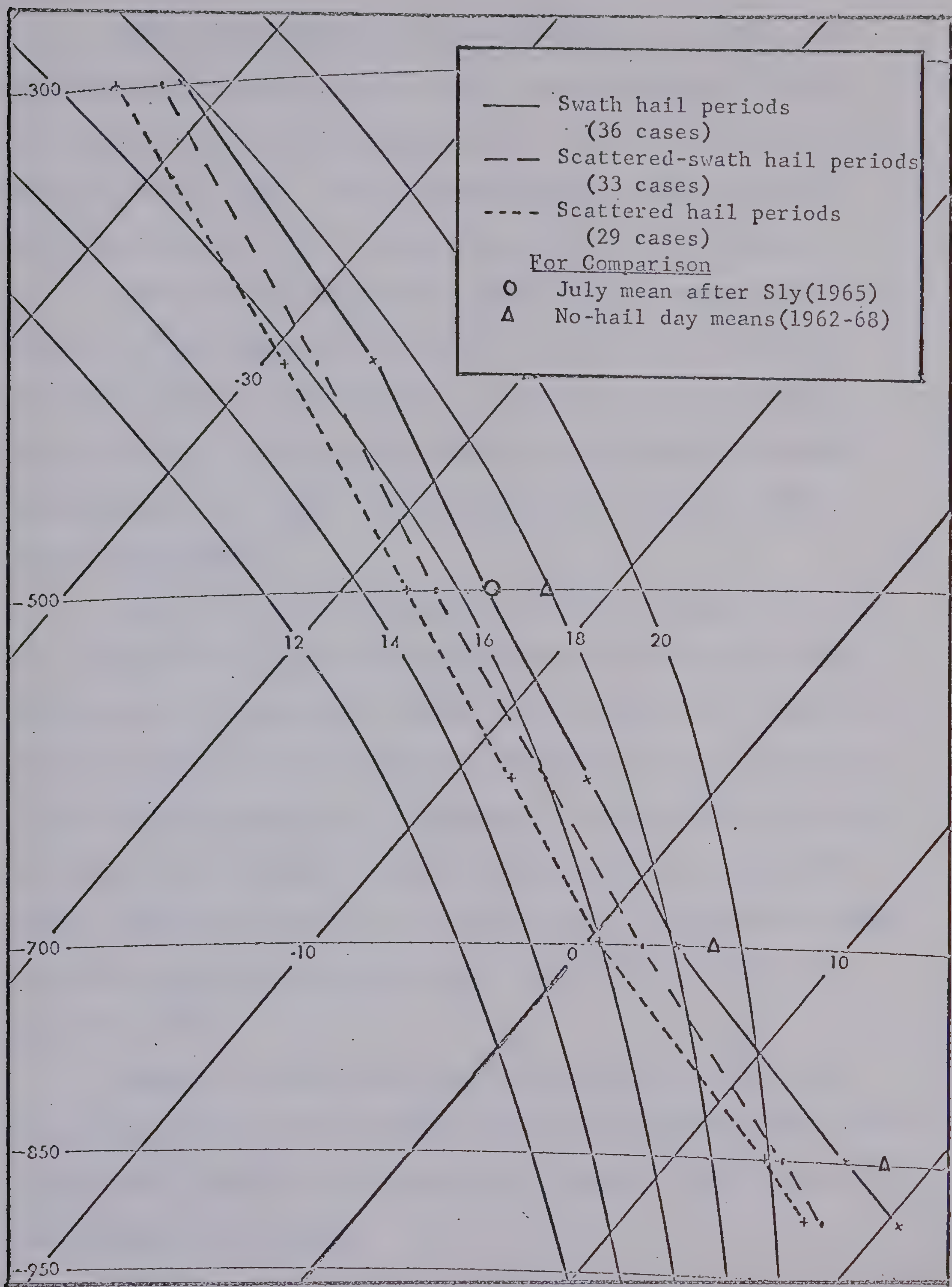


Fig.4.2 Mean temperature profiles for the Calgary region.

Both figures show that the mean temperatures of the swath hail periods are warmer at all levels from the surface to 300-mb than those of the scattered hail periods. At most levels the difference is from 3 to 5C. The mean temperatures of the scattered-swath hail periods are at intermediate values for all levels.

The mean temperatures for no-hail days are warmer than the mean of the hail periods with any hail pattern or the July 1700 MST mean. This is to be expected as a result of the subsidence associated with a surface high pressure area and upper ridge which characterize most no-hail days (see Longley and Thompson, 1965).

<u>700-mb Temperatures</u>

Table 4.1 shows the frequency of 700-mb temperatures per 2C interval for the hail periods associated with each of the three hail patterns. Considerable overlap of the temperature distributions is shown signifying that the 700-mb temperature is not a good indicator of the hail pattern. For example, if the data of both regions are combined, 94 percent of the swath hail periods occurred with 700-mb temperatures equal to or greater than -2C and only 38 percent of the scattered hail periods occurred with 700-mb temperatures less than -2C.

Despite the large overlap it is of interest to note that only eight percent of the scattered hail periods occurred with 700-mb temperatures greater than or equal to 6C compared with 26 percent of the swath hail periods.

Table 4.1 Distribution of 700-mb Temperatures Associated with each Hail Pattern

Hail Pattern	Region	Number of Cases <-6.0C	-6.0- -4.1C	-4.0- -2.1C	-2.0- -.1C	0- 1.9C	2.0- 3.9C	4.0- 5.9C	6.0- 7.9C	>8.0C	Total
Swath	Edmonton		1	3	8	9	12	11	5	5	54
	Calgary		1		5	4	10	3	10	3	36
Scattered Swath	Edmonton	1		9	7	5	6	1	5		34
	Calgary		1	5	5	5	7	4	3	3	33
Scattered	Edmonton	2	3	13	3	6	3	4	2	1	37
	Calgary	2	3	2	4	7	5	4	1	1	29
											223

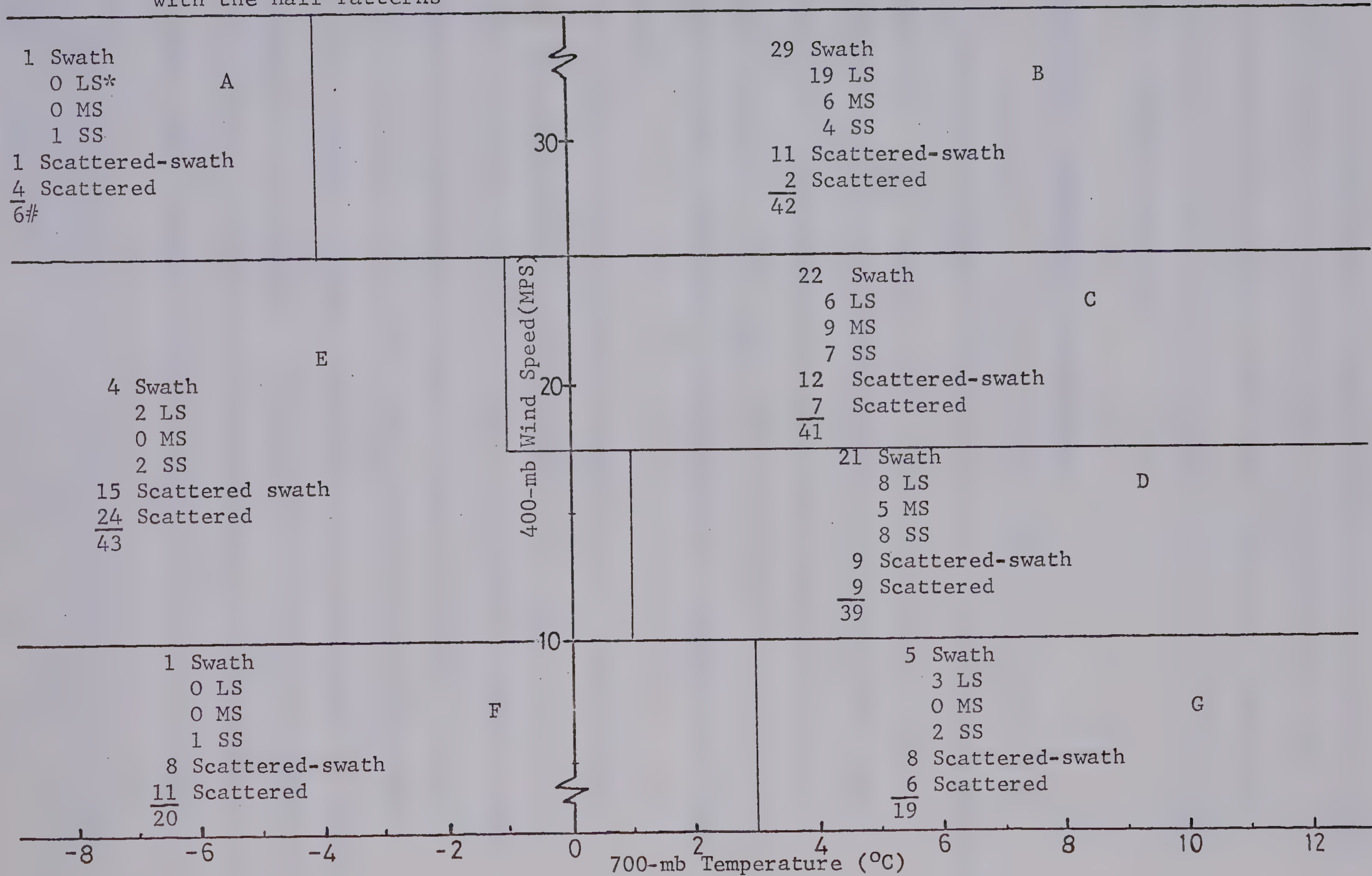
<u>700-mb Temperature - 400-mb Wind Speed Frequency Distribution</u>

Neither the 400-mb wind speeds, discussed in the previous Chapter, nor the 700-mb temperatures clearly distinguish the hail patterns. When they are considered together in a two-way frequency table, as shown in Table 4.2, the hail patterns are better distinguished. For ease of reference, the Table is divided into seven domains labelled A to G.

The proportion of scattered-swath hail periods in each domain is nearly equal, thus creating some doubt about their existence as a separately identifiable group. It appears that in some cases they would have been more correctly identified as swath hail patterns and in others as scattered hail patterns. If the ratio of the swath hail periods to the total hail periods in each domain is considered a measure of the degree of organization or "swathiness" of the scattered-swath hail patterns in that domain, then Table 4.2 provides some criteria for predicting the type of hail pattern likely to result from an anticipated hail-producing system. For 700-mb temperature and 400-mb wind speed combinations in the domains listed, the hail patterns are likely to be:

1) Domain A,E, F - scattered
2) Domain G - swath or scattered with near equal probability
3) Domain C, D - mostly swath
4) Domain B - swath with many long swaths

Table 4.2 Two-way Frequency Distribution of the 400-mb Wind Speeds and 700-mb Temperatures associated with the Hail Patterns



* abbreviations used are: LS-long swath, MS-medium swath and SS-short swath
\# total number of cases is 223 of which 13 are missing because of missing wind data

The foregoing may be summarized by stating that while strong upper winds are a condition for swath, particularly long swath, hail patterns they are not a requirement. Swath hail patterns can also form in the absence of strong upper winds if the 700-mb temperature is sufficiently warm.

Moisture and Instability Considerations

Discussion of convective activity cannot be complete without reference to low-level humidity because of its role in determining instability. It is probably therein that the solution to the production of long hailswaths in the absence of strong vertical wind shear lies. A complete discussion of humidity and instability is beyond the range of this study. Their introduction here is intended only to indicate their role in determining the seasonal distribution of hail.

The low-level moisture distribution in the ALHAS Project Area is variable and not well understood. The variability is reflected by spatial variations in the mean surface 1400 MST wet-bulb potential as illustrated by Table 4.3 after Sly (1965).[1] For each of the three months, June, July and August during the period 1962 to 1964, inclusive, the mean wet-bulb potential temperature at Penhold was higher than at Edmonton or Calgary. Most hailstorms in Alberta are observed to originate in the foothills and it is conceivable that the mean surface wet-bulb potential temperature there is even higher.

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1 The mean wet-bulb potential temperatures for Edmonton and Calgary agree to within .4C of those for the longer period 1953 through 1962 found by Cudbird (1964). No data for Penhold were available for the longer period.

Table 4.3 Mean Monthly 1400 MST Surface Wet-Bulb Potential Temperatures

Month	Mean Wet-Bulb Potential Temperature (°C)		
	Calgary	Penhold	Edmonton
June	16.1	16.3	15.5
July	18.2	18.6	17.5
August	17.3	17.8	16.6

Source: Sly (1965)

When air parcels possessing the mean wet-bulb potential temperatures of the Edmonton station for the months of June, July and August are lifted in the mean monthly environmental temperatures given by the respective dry bulb curves of Fig. 2, Appendix A it is observed that the largest mean positive area occurs in July. From Table 4.4 it is also seen that:

1) 46 percent of the hail periods occurred in July
2) the hail periods in July tended to be with swath hail patterns whereas those in June, when the monthly mean positive area is smaller, tended to be with scattered hail patterns.

In addition, Table 4.3 shows that the monthly mean surface wet-bulb potential temperatures reach a maximum in July whereas Fig. 2, Appendix A shows the mean monthly upper air temperatures continue to rise in August. As a result the troposphere becomes more stable. This is verified by the marked decrease in the number of hail periods in August compared with July in Table 4.4.

Table 4.4 Monthly Frequency of Hail Periods

Month	Swath Pattern		Scattered-Swath Pattern		Scattered Pattern		Total
	Edmonton Region	Calgary Region	Edmonton Region	Calgary Region	Edmonton Region	Calgary Region	
May	2		1		1		4
June	14	7	9	13	16	11	70
July	25	23	15	17	10	12	102
August	12	6	9	3	9	6	45
September	1				1		2
Total	54	36	34	33	37	29	223

There can be little doubt that the magnitude of the positive area influences the thunderstorm intensity despite the uncertainties created by entrainment (see Petterssen, 1956 and Ludlam, 1963). It is also uncertain whether the moisture and temperature conditions at the surface are representative of the air lifted into the thunderstorm although Sly (1964) has found considerable success from this assumption. Nevertheless, the relationships found here between the mean surface wet-bulb potential temperature, the magnitude of the positive area, the degree of organization of the hail patterns and the incidence of hail periods indicate that for individual hailstorms, accurate predictions of their characteristics can only be made with a detailed knowledge of the low-level moisture patterns.

Summary

At most levels from the surface to 300 mb, the mean temperatures for swath hail periods were from 3 to 5C warmer than for scattered hail periods.

The 700-mb temperature was not a good indicator of the type of hail pattern but in combination with the 400-mb wind speed, it was found that swath hail patterns occurred with moderate to light upper winds only when the 700-mb temperature was sufficiently warm, and the lighter the 400-mb winds the warmer were the required 700-mb temperatures.

Variations in stability of the troposphere during the months of June, July and August were reflected by variations in the incidence of hail periods and the degree of organization of the hail patterns. Maximum tropospheric instability in Alberta is reached in July. It was found here that most hail periods occurred in July and that most were with swath patterns whereas in June, when tropospheric instability has not yet reached the seasonal maximum, fewer hail periods were observed, of which many were scattered. The troposphere begins to stabilize in August. Few hail periods were observed for that month.

CHAPTER V

CHARACTERISTICS OF THE HAILSWATHS

Hailstorms in the ALHAS Project Area are frequently observed to originate along the foothills during the afternoon and move eastward. The temporal and spatial distributions of the points of first detection[1] of the hailswaths of the swath hail periods are examined in this Chapter.

Classification of Hailswaths

All hailswaths containing 15 or more unsolicited reports were selected from the swath hail periods[2] only for both regions during the period 1957 to 1968, inclusive.

The swaths were classified into one of four swath length divisions. These were:

1) Short - swaths of length less than 40 miles.
2) Medium - swaths of length 40 to 60 miles.
3) Long - swaths of length greater than 60 miles.
4) Indeterminate - swaths of length less than 60 miles which terminated at the Project Area boundary.

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1 A distinction must be made between point of origin and point of first detection of a hailswath. The point of origin is defined here as the location where the first hail fell. The point of first detection is defined as the location where hail was first reported by a volunteer observer. The respective corresponding times are defined as the time of origin and time of first detection.

2 The hail period requirements that 80 percent of the hail reports of a hail-day fall in one of the two time periods and that a radiosonde sounding be available imposed in Chapter II were relaxed for this study.

Monthly and Regional Frequencies

The monthly and regional frequency of swaths for each swath length division are shown in Table 5.1. Eighty-seven of the 179 swaths occurred in the month of July.

Table 5.1 Monthly and Regional Frequency of Hailswaths per Swath Length Division

Swath Length Division	Region	Number of Hailswaths					
		May	June	July	Aug	Sept	Total
Short	Edmonton	1	6	17	5	1	30
	Calgary		9	21	12	1	43
Medium	Edmonton		4	7	2		13
	Calgary		5	17	7		29
Long	Edmonton	1	9	11	5		26
	Calgary	1	12	12	6	1	32
Indeterminate	Edmonton		1				1
	Calgary		3	2			5
Total	Edmonton	2	20	35	12	1	70
	Calgary	1	29	52	25	2	109

Times of First Detection

Fig. 5.1 shows the percentage hourly frequency of times of first detection of hailswaths for each swath length division. The times of first detection were estimated to the nearest quarter hour from a computer output of the mean onset times per township of each hail-day.

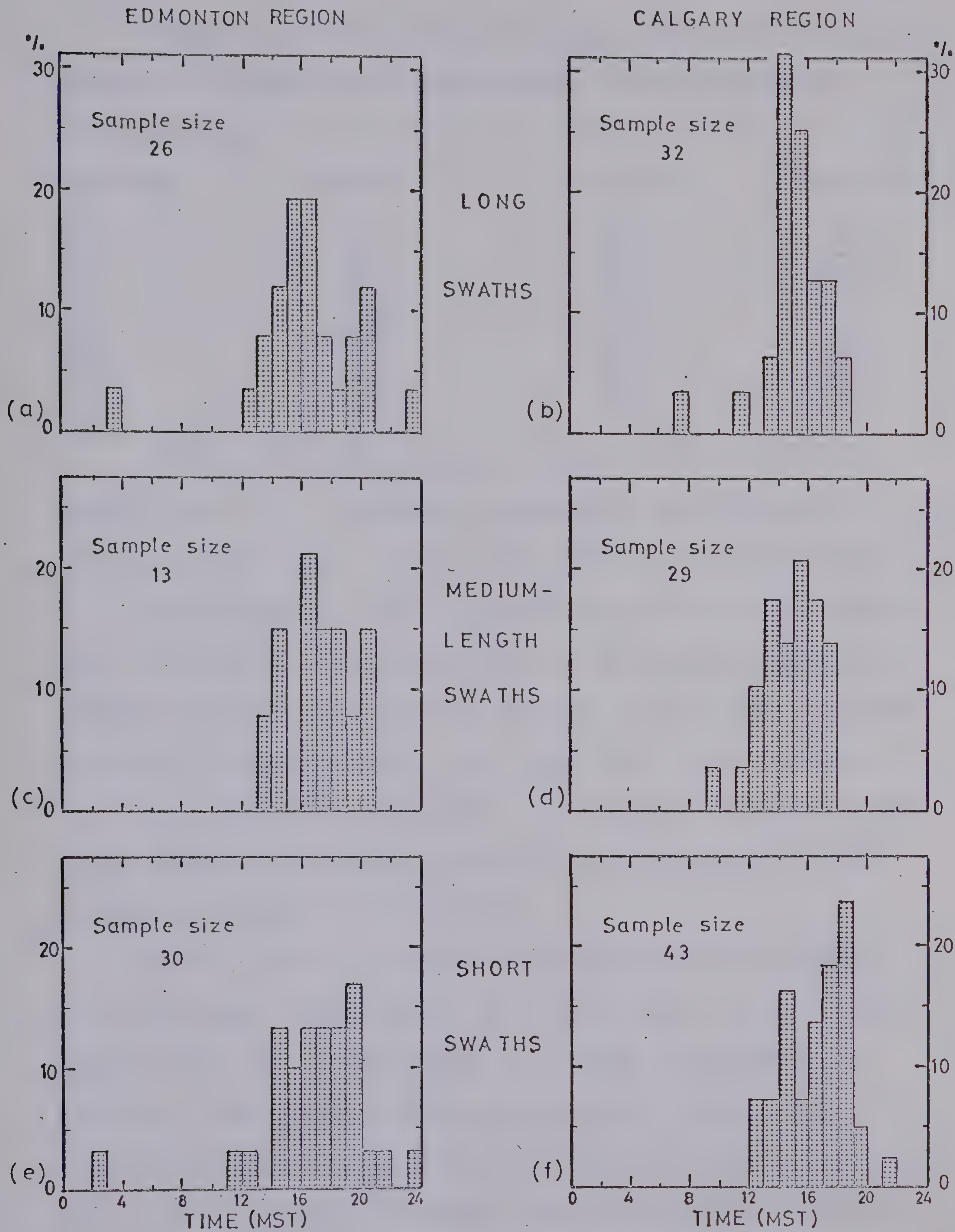

Fig. 5.1 Percentage hourly frequency of times of first detection of hailswaths.

According to Cudbird (1964), the mean hourly temperatures at Calgary for the months June, July and August for the period 1953 through 1962 were:

Hour (MST)	June (^{o}F)	July (^{o}F)	August (^{o}F)
0700	52.4	56.4	52.7
0900	57.7	62.8	59.9
1100	61.0	66.6	64.2
1300	64.0	70.0	67.7
1500	64.8	71.6	69.2
1700	64.5	71.0	68.6
1900	61.8	67.8	64.3
2100	56.2	61.4	58.2

The mean hourly temperatures increase rapidly to about noon and then level off. They reach a maximum about 1500 MST and then slowly decrease to about 1900 MST after which they decrease rapidly.

This period from 1200 to 1900 MST in which the hourly temperatures are relatively uniform and close to the maximum approximately coincides with the period in which the times of first detection shown in Fig. 5.1 are most frequent. This infers that diurnal heating of the lowest levels of the troposphere is a frequent contributing factor to the release of convection necessary for the production of swath-producing hailstorms in Central Alberta.

Other factors are undoubtedly responsible for the formation of a small number of hailstorms. It is conceivable that the secondary maximum in the period 1900 to 2100 MST of Figs. 5.1(a) and (c) may be due to a revitalization of daytime convective clouds through increased radiational cooling of the cloud tops near sunset. In other cases frontal activity is responsible for the release of instability.

The long swaths originated earlier in the afternoon, frequently prior to 1600 MST in the Calgary region and 1700 MST in the Edmonton

region, than did the short swaths. This is probably partly due to the fact that hailstorms originating early in the afternoon have a longer period of warm low-level temperatures which provides a situation favorable for the successive regeneration of new cells.

Points of First Detection

Fig. 5.2 shows the points of first detection of the hailswaths. Clusters containing approximately two-thirds of the points of first detection are shown in regions along the foothills southwest of Calgary, along the foothills from northwest of Calgary northwestward to Rocky Mountain House and to the northeast of Rocky Mountain House. It has been shown previously by Paul (1967) and Williams and Douglas (1963) that these regions are along the western extremities of the populated farmlands. Consequently it is likely that the actual point of origin in many of these cases was further west indicating that the foothills and the forested area north of Rocky Mountain House are hailstorm generation areas.

The mechanism responsible for the formation of hailstorms is difficult to assess without a complete review of the synoptic conditions accompanying each storm. Even then the rapid modification of airmasses during the summer months does not permit an objective classification of frontal and airmass thunderstorms. However, if the distribution of points of first detection in the period 1100 to 1945 MST, inclusive, is compared with the distribution in the period 2000-1045, inclusive, in Fig. 5.2 it is observed that 86 percent of the former are west of the fifth meridian as compared to only 57 percent of the latter. This indicates that most swath-producing

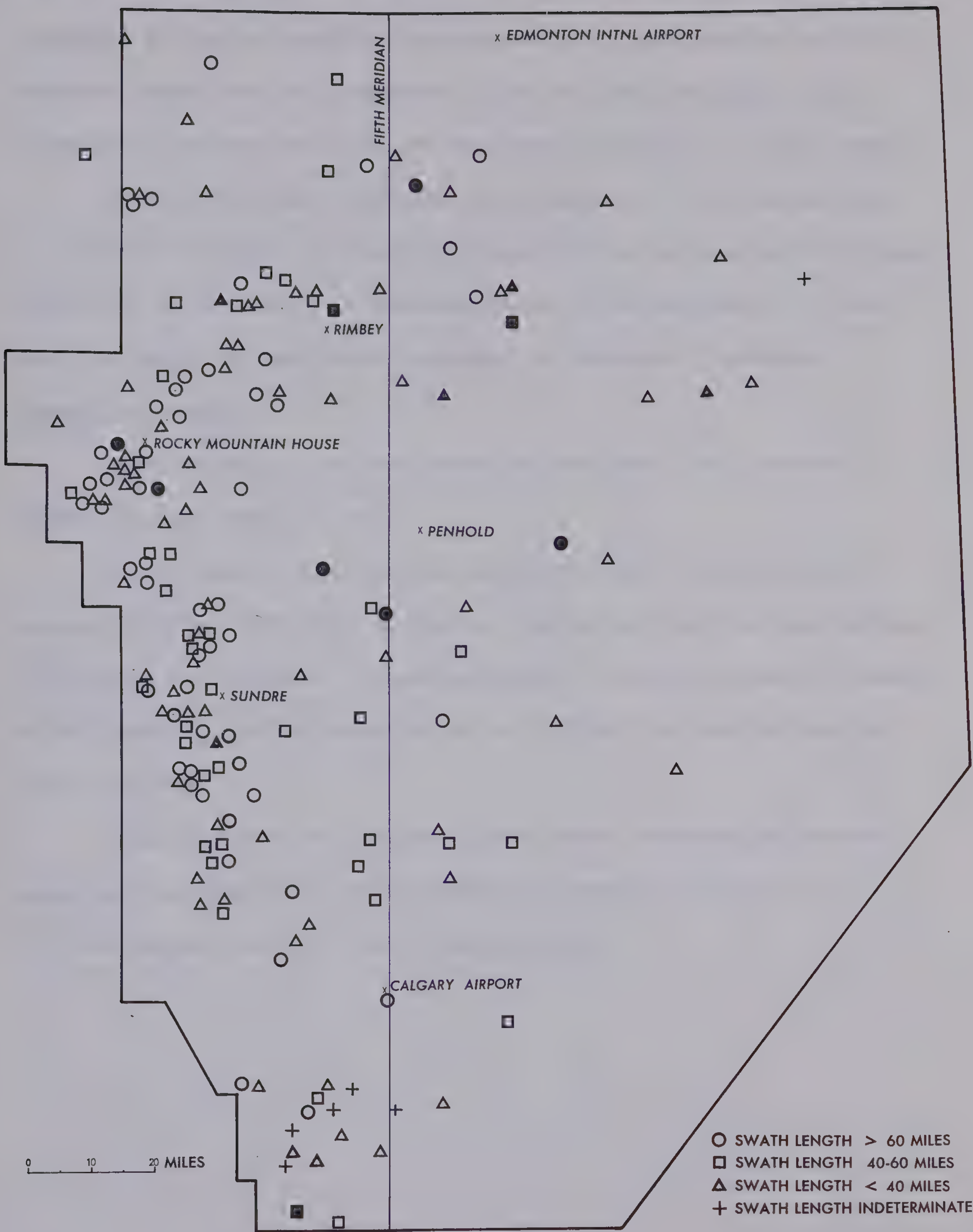

Fig. 5.2 Points of first detection of hailswaths. Shaded symbols indicate time of first detection was between 1945 MST and 1100 MST.

hailstorms emanating from the generation areas are at least partly triggered by daytime surface heating and those originating over the farmlands away from the generation areas are more inclined to be triggered by frontal activity or nocturnal cooling of a cloud layer.

The spatial distributions of the points of first detection of hailswaths in each of the swath length divisions are much the same. Therefore, on the basis of location alone it is impossible to determine the length of hailswath an infant hailstorm will produce.

Summary of Results

Nearly half of the hailswaths of the swath hail periods occurred in the month of July.

Ninety-one percent of the hailswaths were first detected between 1100 and 1945 MST, inclusive, indicating that daytime surface heating was an important trigger mechanism. Longer hailswaths tended to originate in the afternoon prior to 1700 MST and shorter swaths after 1700 MST.

Approximately two thirds of the swath-producing hailstorms emanated from generation areas along the foothills and over the forested region north of Rocky Mountain House.

CHAPTER VI

RELATION TO CROP DAMAGE

In an agricultural area, such as that of the ALHAS Project, hailstorm severity is measured in terms of crop damage. The agricultural factors determining damage at a given location are the type of crop and its stage of growth. Hailstorm factors that are most likely to influence the damage are the size of the hailstones, their impact energy and the amount of hail. The interrelationships between all factors and damage are complex and not well understood.

There is some evidence to indicate that the maximum hail size is a good indicator of damage. It and the number of hail reports are combined here to give a first approximation of the damage associated with each of the three hail patterns.

Maximum Hail Size Distributions

Fig. 6.1 shows the mean percentage frequency distribution of maximum hail sizes for the swath, scattered-swath and scattered hail periods in both regions. The percentage frequency distribution of maximum hail sizes was obtained from the hail-day plots by counting each plotted maximum hail size making appropriate corrections for region size, solicited reports, and, in cases where two hail periods occurred on the same hail-day, the period length.

On the average, more than 70 percent of the hail reports from the scattered hail periods in both regions indicated the maximum size hailstones were pea or smaller and less than five percent indicated that the maximum hail size was walnut or larger. On the other

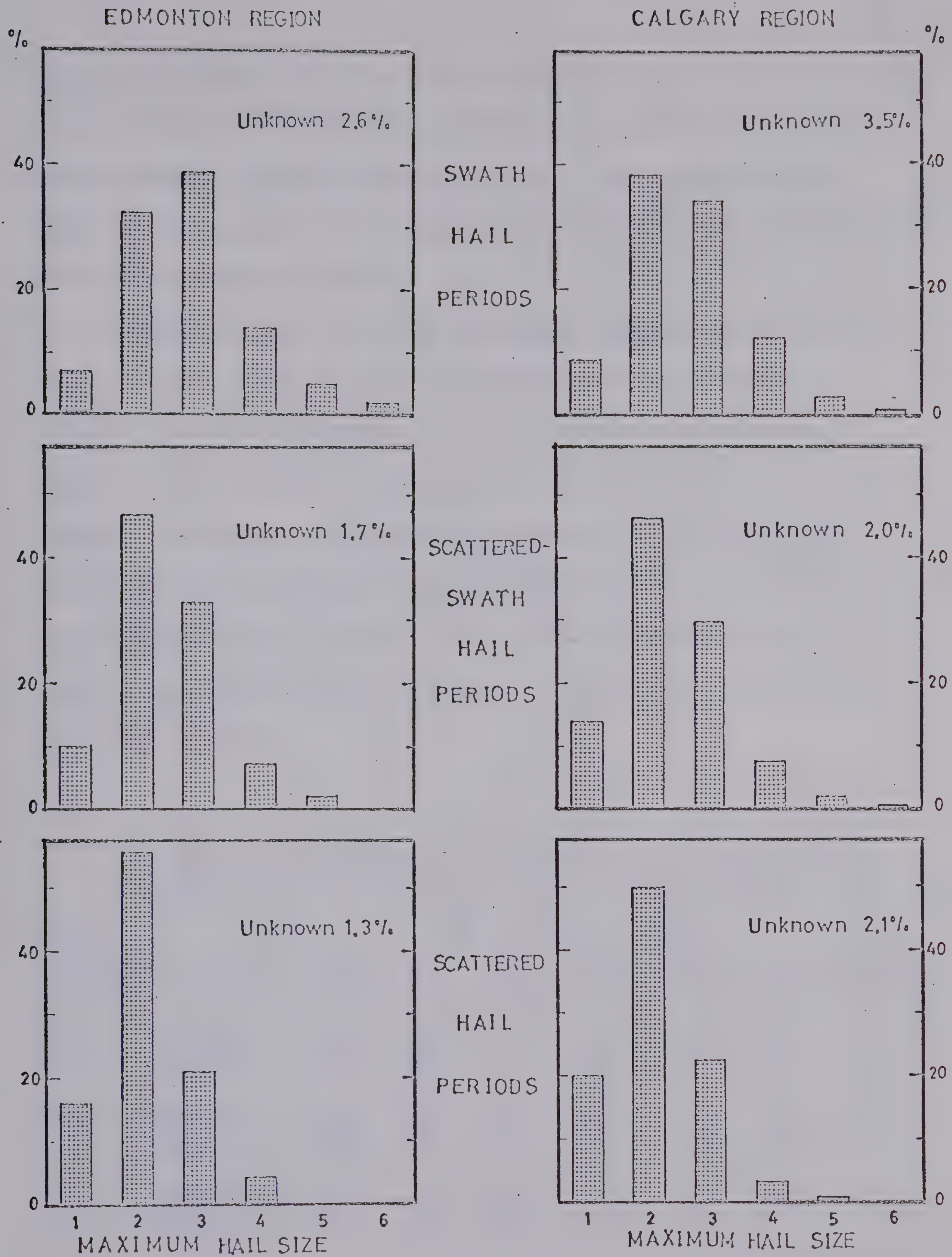

Fig.6.1 Mean percentage frequency distribution of the maximum hail sizes for the swath, scattered-swath and scattered hail periods. Hailstone sizes are: 1-shot, 2-pea, 3-grape, 4-walnut, 5-golfball and 6-larger than golfball.

hand, less than 50 percent of the hail reports from swath hail periods indicated that the maximum size hail was pea or smaller and more than 15 percent indicated walnut or larger. The proportions of small and large maximum hail sizes for the scattered-swath hail periods were of intermediate values.

Table 6.1 shows the mean percentage frequency distribution of maximum hail sizes for the long, medium and short swath hail periods. There is a relation similar to the above between the proportions of small and large maximum size hail and the mean swath length. For example, in the Edmonton Region, on the average 46 percent of the hail reports from the short swath hail periods indicated maximum sizes of pea or smaller and 16 percent walnut or larger compared with 35 and 24 percent, respectively, for the long swath hail periods.

Table 6.1 Mean Percentage Frequency Distribution of Maximum Hail Sizes for the Long, Medium and Short Swath Hail Periods

Swath Length Division	Region	Mean Frequency (Percent) Shot	Pea	Grape	Walnut	Golf-ball	Larger	Unknown (Percent)
Long	Edmonton	4.7	30	38	15	6.8	2.0	3.6
	Calgary	8.7	33	36	13	3.7	.8	4.4
Medium	Edmonton	4.7	31	43	14	6.0	1.1	1.7
	Calgary	8.1	39	35	14	1.4	0.1	1.7
Short	Edmonton	11	35	36	13	2.7	0.6	1.9
	Calgary	10	47	28	8.6	1.8	0.5	3.0

Number of Reports

The number of unsolicited hail reports for each hail period was obtained by manually counting the reports from the hail-day plots with allowance made where necessary for solicited reports. The median number of hail reports associated with each pattern is shown in Table 6.2.

Table 6.2 Median Number of Unsolicited Hail Reports for Swath, Scattered-swath and Scattered Hail Periods

Hail Pattern	Edmonton Region Number of Hail Periods	Edmonton Region Median Number of Hail Reports	Calgary Region Number of Hail Periods	Calgary Region Median Number of Hail Reports
Swath	54	56	36	94
Scattered-swath	34	52	33	48
Scattered	37	34	29	30

On the average, each region received most unsolicited hail reports for swath hail periods and least for scattered hail periods.

Table 6.3 shows that the median number of unsolicited hail reports received for the swath hail periods was proportional to the mean length of the hailswaths. On the average, 144 hail reports in the Edmonton region and 130 in the Calgary region were received for the long swath hail periods compared with 25 and 32, respectively, for the short swath hail periods. The large proportion of long swath hail periods in the Calgary region accounts for the large number of reports per swath hail period for that region in Table 6.2.

Table 6.3 Median Number of Unsolicited Hail Reports for the Long, Medium and Short Swath Hail Periods

Swath Length Division	Edmonton Region Number of Hail Periods	Edmonton Region Median Number of Hail Reports	Calgary Region Number of Hail Periods	Calgary Region Median Number of Hail Reports
Long	23	144	20	130
Medium	14	55	7	33
Short	17	25	9	32

Hail Damage

Summers and Wojtiw (1970), in a study of 5534 reports of crop damage from the period 1956 to 1969, inclusive, found that crop damage was related to the maximum hail size reported. The crop damage estimates were those volunteered by the farmers in the "Remarks" section of the hail report cards (see Fig. 1.2). The damage was classified broadly as slight, moderate to heavy and severe. Their findings are shown in Table 6.4.

Table 6.4 Cumulative Percentage Frequency of Hail Damage in Relation to Maximum Hail Size

Maximum Hail Size	Cumulative Percentage of Reports Indicating Damage Greater than or Equal to Specified Amount		
	Slight	Moderate	Severe
Shot	16.2	2.4	.3
Pea	41.0	10.2	3.2
Grape	74.3	38.9	15.0
Walnut	91.1	60.9	30.9
Golfball or Larger	95.7	78.4	48.9

Source: Summers and Wojtiw (1970)

The cumulative damage is shown to be proportional to the maximum hail size. For example, only 16 percent of farmers reported slight or greater damage with shot as the maximum hail size compared with 96 percent with golfball or larger.

Damage Per Hail Period

According to the Alberta Hail Studies 1969 Field Program,[1] the density of unsolicited hail reports from surveyed hailstorms has varied from 1 report per 20 square miles to 1 report per 30 square miles over the period 1965 to 1969, inclusive, with the exception of 1968 when it was 1 per 51 square miles due to a July mail strike.

[1] Renick, J.H. (ed.), 1970: Alberta Hail Studies 1969 Field Program. Edmonton, Research Council of Alberta, Hail Studies Report 69-1, p. 11.

Considering one hail report per 20 square miles representative of the period under study, Table 6.5 gives the median areal extent of hail for the hail periods with each of the hail patterns on the basis of the data given by Tables 6.2 and 6.3. Due to the great variation in areal extent of hail within the swath hail periods, it is more meaningful to compare the swath length hail periods individually with the scattered-swath and scattered hail periods. Hailfall in long swath hail periods covered the largest area, roughly 2600 to 2900 square miles. Hailfall for the medium length swath and the scattered-swath hail periods covered approximately equivalent areas, about 900 to 1100 square miles (assuming the sample size of Calgary medium length hail periods too small to be representative). Hailfall for the short swath and scattered hail periods was least extensive, covering approximately 500 to 700 square miles.

Table 6.5 Median Areal Extent of Hail for the Hail Periods with each Hail Pattern

Hail Pattern	Area (Sq. Mi.) Edmonton Region		Calgary Region	
Swath	1120		1880	
Long		2880		2600
Medium		1100		660
Short		500		640
Scattered-Swath	1040		960	
Scattered	680		600	

If it is assumed the density of one hail report per 20 square miles is equally applicable to each maximum hailsize reported, that is, the farmer's decision to contribute a hail report is not influenced by the size of the largest hailstones that he receives, the data of Fig. 6.1 and Tables 6.1, 6.4 and 6.5 may be used to estimate the proportion of the areal extent subjected to each level of damage. The results for the Edmonton region are shown in Table 6.6.

Table 6.6 Cumulative Areal Extent of Damage per Hail Period in the Edmonton Region

Hail Period	Median Areal Extent of Hail(Sq. Mi.)	Area Subjected to Damage Greater than or Equal to that shown (Sq. Mi.)		
		Slight	Moderate	Severe
Swath	1120	700	310	170
Long	2880	1820	980	440
Medium	1100	700	380	160
Short	500	280	140	60
Scattered-swath	1040	560	240	100
Scattered	680	320	120	40

The long swath hail periods subjected the largest area to damage. For these, the median area subjected to slight or greater damage was 1820 square miles, to moderate or greater damage 980 square miles and to severe damage 440 square miles. For the short swath and scattered hail periods, the median area subjected to slight or greater damage was approximately 280 to 320 square miles,

to moderate or greater damage approximately 120 to 140 square miles, and to severe damage approximately 40 to 60 square miles.

The effect of the maximum hail size-damage relationship has been to increase the disparity in the area subjected to damage between the long swath hail periods and the short swath and scattered hail periods over that which would have existed if the maximum hail size distribution had been identical for all hail periods. Nevertheless, the most important factor determining the area subjected to each level of damage during a hail period is the overall areal extent of hail.

Average Annual Damage

An estimate of the annual area subjected to the three levels of damage associated with each hail pattern is shown in Table 6.7. The cumulative areas subjected to each level of damage were obtained by multiplying the values of Table 6.6 by the mean annual occurrences of the various hail periods.

Table 6.7 Median Areal Extent of Damage per Hail Season in the Edmonton Region

Hail Pattern	Mean Annual Frequency of Occurrence	Annual Area Subjected to Damage Greater than or Equal to that Shown (Sq. Mi.)		
		Slight	Moderate	Severe
Swath	4.51	4720*	2525	1125
Long	1.92	3500	1880	850
Medium	1.17	820	445	190
Short	1.42	400	200	85
Scattered-swath	2.83	1580	680	285
Scattered	3.08	985	370	125
Total		7285	3575	1535

* Values shown for swath hail periods are the sum of the values given for the long, medium and short swath hail periods.

In the average hail season, the long swath hail periods subjected much more area to damage than any of the other hail periods. They subjected roughly 3500 square miles to slight or greater damage, 1880 square miles to moderate or greater damage and 850 square miles to severe damage. These values are approximately 50 percent of the respective annual totals. The scattered-swath hail periods subjected the second largest area to each level of damage but these only account for about 20 percent of the respective totals.

Accuracy of the Damage Estimates

Most of the assumptions made in arriving at the values shown in Tables 6.6 and 6.7 tend to affect the results for each pattern in the same manner. For this reason, and because of the number of assumptions made, the relative orders rather than the magnitudes shown should be used to assess the damage associated with each hail pattern.

It is probable that the values shown for Table 6.7 underestimate the annual areas subjected to each level of damage because they are based on the median rather than the larger mean areal extent of hailfall per hail period, and because some hail-producing systems failed to qualify as hail periods under the requirements given in Chapter II, and as a result were excluded from the above analysis.

The best alternative estimate of the actual hail damage per hail period is that obtainable from hail insurance claims and it is also only rough approximation. According to Summers (1966) the Alberta Hail Insurance Board underwrites 60 to 80 percent of the hail insurance in Alberta, but only 10 to 20 percent of the farmers are estimated to insure against hail loss. Even if the damage could be accurately estimated from this small a proportion of the farmers, the Alberta Hail Insurance Board claim records for the period 1957 through 1968 are not in a form which permit evaluation of the damage in localized areas of the Province such as those corresponding to the Edmonton and Calgary regions of this study.

Summary of Results

The degree of organization of the hail pattern in each hail period was found to be related to both the number of hail reports and the skewness of the frequency distribution of maximum hail sizes. Most hail reports were received for swath hail periods and least for scattered hail periods. The swath hail periods tended to have the highest proportion of walnut and larger maximum size hailstones and the smallest proportion of pea and smaller maximum size hailstones. The scattered hail periods tended to have the highest proportion of pea and smaller maximum size hailstones and the smallest proportion of walnut and larger maximum size hailstones.

For the swath hail periods alone, similar relationships were found between the mean swath length and both the number of hail reports and the proportions of large and small maximum hail sizes.

The area subjected to each of the cumulative levels of crop damage, slight or greater, moderate or greater and severe for an average long-swath hail period was roughly three to four times that for average medium length and scattered-swath hail periods and roughly six to eleven times that for average short swath and scattered hail periods.

A rough approximation showed that about half of the total annual area subjected to hail damage is caused by a relatively small number of long swath hail periods.

CHAPTER VII

COMPARISON WITH OTHER RESEARCH

Many articles have been written on hail research in Alberta and in other parts of the world. The results found in this study support the findings of many authors but are in disagreement with others.

Wind Direction

500 mb Wind Direction

Longley and Thompson (1965) studied hailfall over that part of Alberta south of the North Saskatchewan River from 1959 to 1963, inclusive. They observed that the 500-mb winds were from the southwest quadrant and greater than 30 knots for 63 percent of their major hail cases, 48 percent of their minor hail cases and 32 percent of their no-hail cases. Their classification of major and minor hail-days was based on a subjective interpretation of hail reports received by the Alberta Hail Studies Project, hail insurance claims and other sources.

Similar results have been observed in Colorado. Schleusener (1962) and Beckwith (1960) found that the wind direction at 500 mb on hail-days favored WSW. Modahl (1969) carried the analysis further and showed that the mean 500-mb wind on hail-days with golfball or larger hail was about 250° whereas for other hail-days with smaller hailsizes the means were between 265 and 285°.

The findings in Alberta and Colorado indicate that the most desirable 500-mb synoptic feature for the more destructive hailstorms

in these areas is a trough to the west.

This conclusion contradicts Frisby (1964) who, from observations in South Dakota, states that hailswaths tend to be "in tight and narrow formation" when associated with northwesterly winds on the east side of an upper ridge, a situation which she claims produces strong jet stream winds. She does say, however, that hail patterns are also "well organized but in looser formation" when associated with an approaching upper-level trough because the jet stream winds associated with this synoptic situation are lighter. She further indicates that hailfall is patchy and randomly distributed when the upper winds are about 15 metres per second.

Because her findings with respect to upper-level wind speeds are similar to those found here but those with respect to direction are different, it is probable that wind directions above 700 mb have no role in the hailstorm dynamics. It is likely that with these favored wind directions, other parameters frequently occur that encourage hailstorm production. In Alberta the association of factors leading to instability due to daytime surface heating, and vertical wind shear would frequently favor hailstorm development with an approaching upper trough. Frisby has indicated that frontal activity is a frequent cause of hailstorms in South Dakota, and that upper winds are strongest from the northwest quadrant. It is therefore possible that frontal activity and strong vertical wind shear both frequently occur in association with northwest upper winds there.

Deviation From Swath

The deviation of the hailstorms to the right of the upper-level winds confirms the earlier findings of Carte (1963) for 12 swaths in the ALHAS Project Area during the period 1957 to 1960, inclusive. He found that the swath orientations were "mostly about 30 degrees to the right of the upper winds" at 700, 500 and 300 mb. Elsewhere, Frisby (1963) observed that hailstorm swaths of the Upper Great Plains of the United States were frequently about 20 degrees to the right of the 500 mb winds. Carte (1966) states that hailstorms in Transvaal, South Africa produce swaths that deviate to the left of the upper winds, though frequently the swaths are short and difficult to define. However, for the northern hemisphere it seems reasonable to conclude that most hailswaths deviate about 20 to 30 degrees to the right of the 500-mb winds.

With this deduction, examination of Fig. 3.1(b) and 3.2(b) reveals why Powell (1961) observed that hailswaths in the southern part of Alberta tended to be oriented WNW-ESE and those in the central region tended to be oriented WSW-ENE.

Directional Shear

Newton and Newton (1959) and Browning (1964) separately produced thunderstorm models that explained the deviation of the hailswath from the 500-mb wind flow. Both required that the winds relative to the cloud veer with height such that those near the surface feed into the cloud through its right forward flank and the upper tropospheric winds push the cloud from its rear.

Tables 3.4 to 3.9 of Appendix B indicate that there was little

directional wind shear in the 700 to 200 mb layer associated with any of the hail patterns of this study. In the surface to 700 mb layer there were some winds from the southeast quadrant near the surface as the models required but these did not represent the majority. It must be concluded that there is little evidence to indicate that the Newton and Newton or the Browning models are often applicable to the hail producing thunderstorms of Alberta.

Miller (1967) also suggested that veering of the wind with height, particularly the case of a low-level jet overridden by an upper-level westerly jet, is an important forecast parameter for severe local storms in the central and eastern United States. It, likewise, is inapplicable to Alberta hail storms.

Wind Speed

The Influence of Strong Upper Winds

The influence of strong upper winds has been examined by many authors resulting in superficially opposing views.

One view contends that severe hailstorms are associated with strong upper winds. Dessens (1960) found that destructive hailstorms in southwest France were associated with strong winds in the 500 to 200 mb layer and that less destructive hailstorms were associated with lighter winds in this layer. Schleusener (1963) observed that severe hail in Colorado was closely correlated with strong winds aloft. Modahl (1969), also using Colorado data, observed that upper winds associated with hailstorms that produced heavy and moderate hail were greater than those with thunderstorms that produced light hail or no hail.

On the other hand, Ratner (1961) found there was no significant difference in the mean wind speeds at 500-mb and 250-mb between hail producing and non-hail producing thunderstorms in any of seven areas of the United States. Proppe (1965) reached a similar conclusion for severe hail-days and "milder thunderstorm days" for the ALHAS Project Area on the basis of 1964 data.

Closer examination of the data of each author reveals that the views are not so divergent as a cursory review would suggest. All differ in their standard of hail intensity and there is wide variation in their hail observation networks. In addition, both Ratner and Proppe use significance tests on their data. Modahl, Dessens and Schleusener merely note that the upper winds with severe hailstorms are stronger.

It therefore appears that the wind speed profiles found in this study are not atypical of those found elsewhere. Wind speeds at levels from 600 mb to the tropopause are on the average stronger with long swath, large hail producing hailstorms than with others.

Wind Components

Takeda (1969) produced a two-dimensional thunderstorm model in which the life of a thunderstorm is shown to be determined by the ambient wind conditions. The condition favoring long lasting thunderstorms is a reversal of the direction of the vertical wind shear within a critical height range in the lower troposphere. In contrast, strong vertical wind shear of constant sign favors dissipation of the cloud in a short time period without regeneration of another.

The median wind component profiles for long swaths in Figs. 3.6 and 3.7 are in agreement with Takeda's predicted wind shears for long lasting thunderstorms. They both show reversal of wind-shear about 1500 feet above ground. The wind component profile for the short swaths in the Edmonton region supports his model for short lived thunderstorms but that from the Calgary region does not, possibly due to the small sample size.

The results found here, while encouraging, cannot be regarded as conclusive support for the model because they assume that the light low-level winds at the radiosonde station were representative of those throughout the region. It was unlikely that this was the case.

The Influence of Temperature

The 700-mb temperatures were examined by Longley and Thompson (1965) for Alberta hailstorms. They found that major hail fell four out of 87 times when the 700-mb temperature at Calgary was less than -2 C and that minor hail fell 15 out of 97 times when the 700-mb temperature was less than -1 C. These values approximate those shown in Table 4.1.

Frisby (1965), in comparing hailstorms of the tropics with those at mid-latitudes, concluded that a requirement for the swath-producing hailstorm was strong vertical wind shear and "the greater the shear, the better organized the swath". The findings here do not wholly support this conclusion. Table 4.2 infers that while most long and medium-length swaths are associated with 400-mb winds greater than 25 mps they also occur with lighter upper winds when the 700-mb

temperature is sufficiently warm. The lighter the 400-mb wind the warmer must be the 700-mb temperature for hailswaths to be formed.

Swath Characteristics

Many authors have studied the onset times of origin of hailstorms. Beckwith (1960) examined the times of hailstorm onset in Colorado for the period 1949 to 1958, inclusive. He found that two-thirds of the hailstorms commenced between 1300 and 1800 MST inferring that daytime surface heating is also an important trigger mechanism there. His results indicate that fewer hailswaths originate in Colorado in the period 1800 to 2000 MST than a combination of all length divisions of Fig. 5.1 would indicate for Alberta. This is probably because most hailswaths occur in May and June in Colorado whereas most hailswaths in Alberta occur in late June and early July when the days are longer.

The generation areas found here with the swath-producing hailstorms are not so evident in South Dakota and Illinois. Frisby (1962) indicates that the points of hailswath origins in South Dakota are scattered and the proportion over low ground is approximately the same as that over high ground on a per area basis. She states that many of the hailstorms there are caused by frontal activity and this may explain the more random distribution of points of origin. Changnon (1962) in a study of the 128 most severe summer hailstorms in Illinois during the 1910 to 1959 period, found that 64 percent of the origins were in United States Weather Bureau areal divisions along the Mississippi River Valley. The variation in relief there is insufficient to draw a comparison regarding the effects of topography.

It would be of greater interest to compare the points of hailswath origins here with those of Colorado where similar topographical features, times of hailswath onset and upper wind patterns conducive to hailswath formation exist. Unfortunately, no such data are available.

Damage

The existence of a relationship between maximum hail size and crop damage is a matter of some debate. Changnon (1966), in a study of 738 hail reports from volunteer hail observers in Central Illinois, found a relationship between maximum hailstone size and degree of crop damage. The relationship is not so well defined as that found by Summers and Wojtiw (1970) shown here as Table 6.4. For instance, Changnon found that in 41 percent of his much-damage cases the maximum size hailstone reported was one-half inch or less in diameter. Summers and Wojtiw found only 3.5 percent of their severe damage cases were due to pea size (half-inch) or smaller maximum size hailstones. Changnon (1969) later discounted the size of the hailstones as an indicator of crop damage in favor of the number of hailstones per square foot. Nevertheless, it is difficult to disregard the findings of Summers and Wojtiw, particularly in view of the large sample size on which they base their results and the difference in crop types between Alberta and Illinois.

CHAPTER VIII

CONCLUDING REMARKS

Summary

This study has attempted to identify and characterize the most destructive hailstorms from the population of all hailstorms in Central Alberta.

Hail periods were selected from the farmer-volunteered hail reports to the Alberta Hail Studies Project for the period 1956 through 1968. With the assistance of computer processed hail-day plots the hail periods were divided into three groups according to the degree of organization of the pattern of the plotted hail reports. These were: swath for those patterns in which distinct swaths were evident, scattered for those in which no swaths were evident and scattered-swath for those in which poorly defined swaths were evident. The swath hail periods were subdivided into three divisions on the basis of the mean length of the swaths, namely: long, medium-length and short.

It was found that the greatest area subjected to hail damage was associated with the long swath hail periods. The area subjected to each of the cumulative levels of hail damage, slight or greater, moderate or greater and severe for an average long swath hail period was roughly three to four times that for average medium length or scattered hail periods, and six to eleven times that for the short swath and scattered hail periods.

On an annual basis, it was found that roughly fifty percent of the total area subjected to damage was associated with a small number of long swath hail periods.

The median 500-mb wind directions for the swath hail periods were 242° and 250°, and for the scattered hail periods 250° and 273° in the Edmonton and Calgary regions, respectively. In the southern part of the Project Area the 500-mb wind directions were concentrated between 240 and 280° whereas in the northern part they were uniformly distributed over the range 180 to 300°. Because the hailswath directions were about 25° clockwise from the 500-mb wind directions, the orientation of the hailswaths in the southern part was frequently WNW-ESE whereas the orientation of those in the northern part was more variable but tended to be WSW-ENE.

The wind directions associated with all hail patterns were nearly constant with height from 700 to 200 mb. Below 700 mb no consistent changes in wind direction with height were evident with any hail pattern. These observations provided little support for the Newton and Newton (1959) or Browning (1964) hailstorm models which require that the environmental winds veer with height from the surface to the upper troposphere. They also indicate that Miller's (1967) low-level jet is not frequently associated with Alberta hailstorms.

The median wind components parallel to the swath axis were stronger at the 500-mb and higher levels for the long swath hail periods than for the short and medium swath hail periods. It was also found that the median vertical wind shear component for the long swath hail periods reversed direction about 50 mb above the

surface. This provides some support for the wind profiles of Takeda's (1969) long-lived thunderstorms but a conclusive comparison could not be made because it is not known how well the low-level winds examined here represented those in the vicinity of the hailstorms.

It was found that the mean environmental temperatures were from 3 to 5C warmer for swath hail periods than for scattered hail periods at most levels from the surface to 300 mb. Similarly the mean wind speeds above 700 mb were stronger for the swath hail periods than for the scattered hail periods.

Despite these differences neither the temperature nor the wind speed alone at any level clearly distinguished the hail patterns. However, when the 700-mb temperature and the 400-mb wind speed were considered together in a two-way frequency table a better indication of the hail pattern was given. For the 700-mb temperatures and 400-mb wind speeds given below, the hail patterns were found to be:

700-mb Temperature (^{o}C)	400-mb Wind Speed (MPS)	Hail Pattern
< -4	> 25	predominantly scattered
< -1	17.5 - 25	" "
< 1	10 - 17.5	" "
< 3	< 10	" "
> 3	< 10	both swath and scattered
> 1	10 - 17.5	mostly swath
> -1	17.5 - 25	" "
> -4	> 25	predominantly swath with many long swaths

It was found that 91 percent of the hailswaths of the swath hail periods were first detected between 1100 and 2000 MST inferring that daytime surface heating was an important trigger mechanism. Hailstorms that produced hail prior to 1700 MST were found to have a higher probability of producing long swaths than those which first produced hail after 1700 MST.

Approximately two-thirds of the swath-producing hailstorms originated in generation areas located in the foothills southwest of Calgary, along the foothills from northwest of Calgary northwestward to Rocky Mountain House and in the forested area north of Rocky Mountain House.

Conclusions

What features characterize destructive hailstorms in Central Alberta? This study has provided some answers to this question but was unable to provide a complete solution.

Hail periods which subject the largest area to damage are those in which long hailswaths are produced. Hailstorms occurring during these hail periods are vigorous and well developed, are capable of producing very large hailstones, and tend to develop in the foothills prior to 1700 MST moving out over the farmlands in a direction 25^{o} clockwise from the 500-mb wind.

While these hailstorms are easily characterized, they are not easily predicted. Neither the upper-level wind directions, wind speeds nor the temperatures distinguish these hail periods from other hail periods. Strong upper winds appear to have a role in the production of some long swaths but not all. It is concluded that strong

upper winds are a condition but not a requirement for the production of long hail swaths.

Recommendations

It is recommended that future research be focussed on the hailstorms producing long swaths because these storms must successfully be modified if hail suppression is to achieve any significant results.

Because daytime surface heating is a frequent trigger mechanism for the long swath-producing hailstorms, the magnitude of the potential instability must be better understood over the Project Area, particularly west of the fifth meridian, if these storms are to be predicted before they develop. This can be achieved only with a better knowledge of the low-level moisture field.

For the present it is recommended that an existing instability index and the 400-mb wind speed be considered together for the purpose of predicting the degree of convective activity. This study suggests that the ratio of the number of hail reports of maximum size walnut and greater to the number of hail reports of pea size and smaller might indicate the degree of convective activity for correlation purposes.

While it has been shown that the most important factor determining the areal extent of hail damage in a hail period was the overall areal extent of hailfall, the localized nature of high-value crops may not mean this also indicates the greatest value loss. For that reason there is a need to understand better which hailfall characteristics determine crop damage. This might be approached

by comparison of the farmer contributed hail reports to the Alberta Hail Studies Project with hail insurance claims for a limited number of hailstorms or by comparison of a small scale but detailed study of hailfall characteristics with the crop-loss evaluations of an experienced hail insurance adjustor.

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APPENDIX A

The tables and figures in this Appendix give wind direction frequencies and temperature profiles for the months of June, July and August, the months for which nearly all hail is reported in Alberta. The tabulations are from 1700 MST Radiosonde data. For the Calgary region the sample comprises the entire period of operation of the Radiosonde station from 1962 to 1968, inclusive. For the Edmonton region, the data is from the period 1961 to 1968, inclusive.

Calm conditions and missing data could not be considered in the calculations of wind direction frequencies in Fig. 1. The percentage frequencies of these conditions are listed below in Table 1.

Table 1 Percentage Frequency of Calm and Missing Winds for all Days at 1700 MST

Month	Level (mb)	Edmonton (1961-68) Calm	Edmonton (1961-68) Missing	Calgary (1962-68) Calm	Calgary (1962-68) Missing
June	500	.0	1.3	1.8	1.8
	850	.0	.0	1.8	1.3
July	500	.0	2.4	.5	1.6
	850	.4	.4	2.1	.0
August	500	.0	4.4	.5	1.0
	850	.4	1.6	.5	1.0

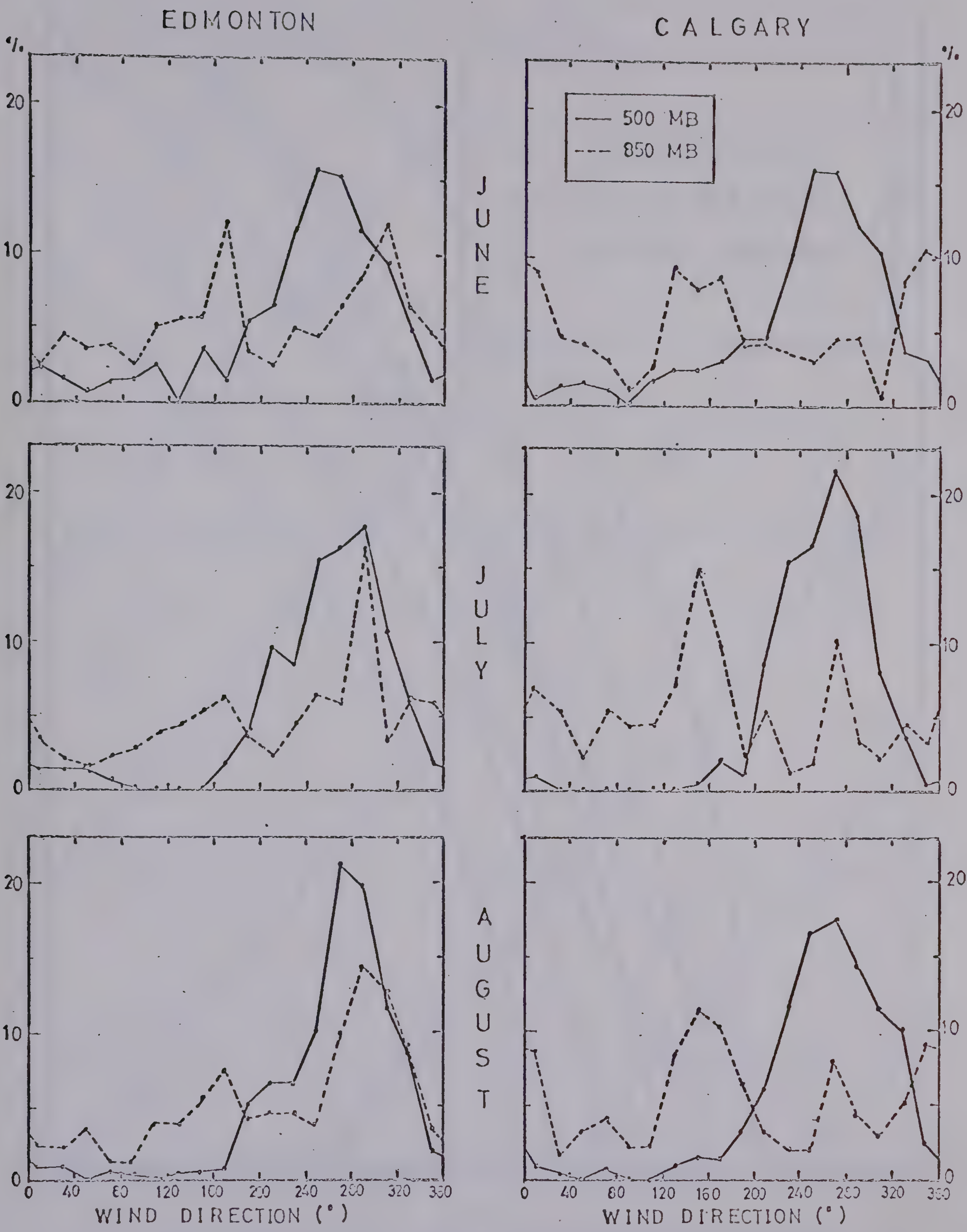

Fig. 1 Percentage frequency of 850-mb and 500-mb wind directions for June, July and August of 1961 through 1968. See Table 1 on previous page for percentage frequencies of calm and missing winds.

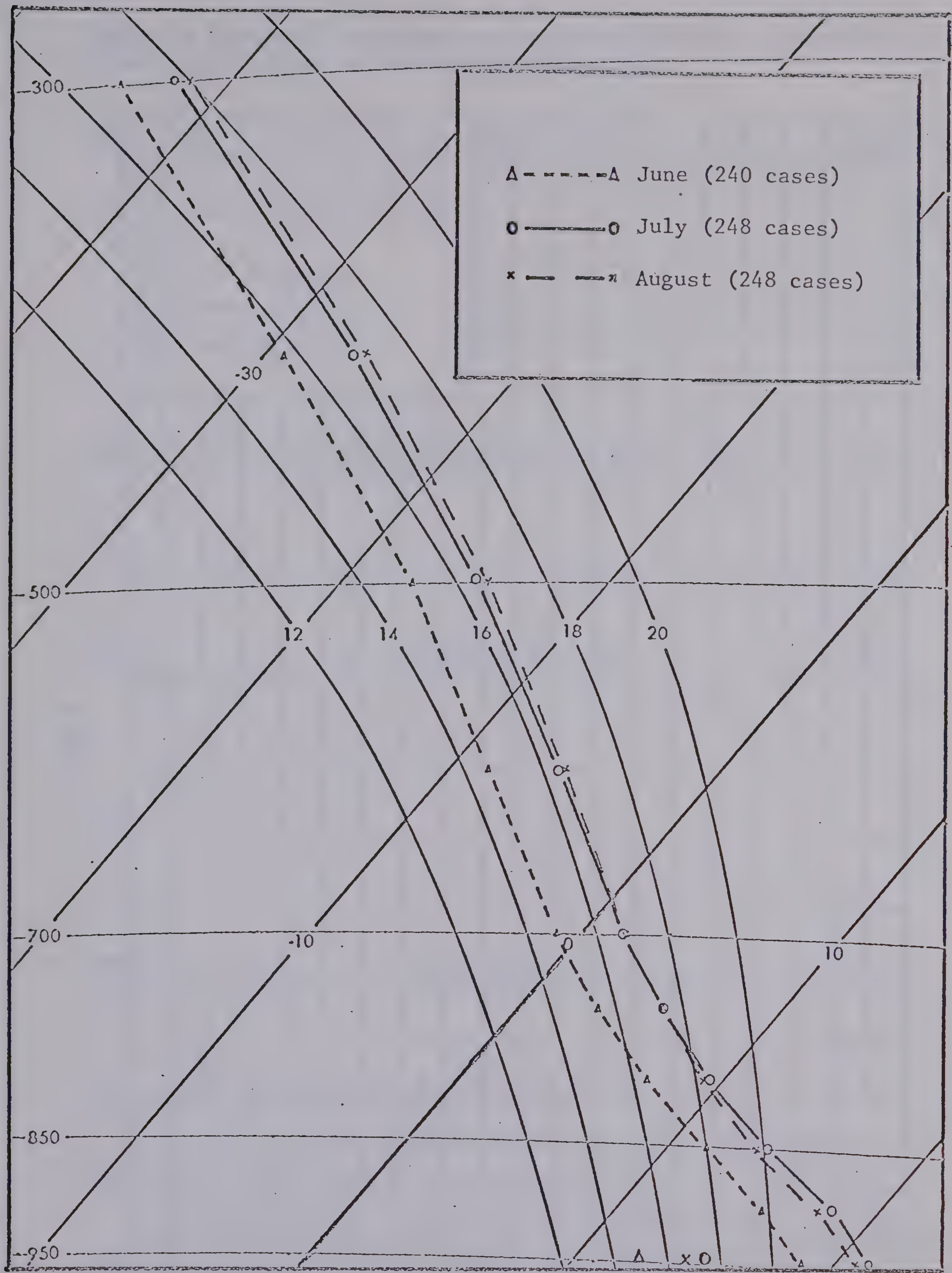

Fig. 2 1700 MST mean monthly temperature profiles at Edmonton for the period 1961-68, inclusive. Symbols at 950 mb indicate mean 1400 MST surface wet-bulb potential temperatures for the respective months after Cudbird(1964).

Table 3.4 Frequency Distributions of Surface and Upper-Level Wind Directions Relative to 500-mb Wind Direction.

Region: Edmonton

Pattern: Swath

No. of cases: 54

MBS	161–180	141–160	121–140	101–120	81–100	61–80	41–60	21–40	1–20	0–19	20–39	40–59	60–79	80–99	100–119	120–139	140–159	160–179	CALM	MISSING
200								4	14	14	1	1		1		1				18
300						1	2	6	15	17	1	2	1							9
400						1		5	22	20	2	1	1							2
500																				
600							1	4	18	24	4	3								
700		1			1	2	2	5	12	14	12	4	1							
					3	1	3	9	6	14	6	4	6	1		1				
800	1			3	2	2	5	9	6	6	7	3	7	1			2			
	2	2	4	4	1	3	5	3	2	5	4	2	4	4	2	5		2		
900	3	4	2	2		7	3		2	3	4	4	1	6	6	4	3			
		2	4	2	4	2	3	2	2		4	4	6	5	5	6	2	1		

<COUNTER-CLOCKWISE — | — CLOCKWISE —>

DEVIATION FROM 500-MB WIND (°)

Table 3.5 Frequency Distributions of Surface and Upper-Level Wind Directions Relative to 500-mb Wind Direction.

Region: Calgary

Pattern: Swath

No. of cases: 36

MBS	161–180	141–160	121–140	101–120	81–100	61–80	41–60	21–40	1–20	0–19	20–39	40–59	60–79	80–99	100–119	120–139	140–159	160–179	CALM	MISSING
	← COUNTER-CLOCKWISE									CLOCKWISE →										
200							2	3	5	5	2	1								18
300							3	1	10	7	3					1				11
400								3	16	11	2									4
500																				
600								4	17	11	4									
700							5	4	14	6	5	1	1							
					3	4	4	2	9	4	6	1		1				1	1	
800	1		3	3	2	6	2	1	2	1	5	2	4		2	1			1	
	2	1	5	3	2	4			1	2	1	2	3	2	4		1	3		
900	3	2	5	1	4		2		3	1	2	1	3	5		1	1	2		

DEVIATION FROM 500-MB WIND (°)

Table 3.6 Frequency Distributions of Surface and Upper-Level Wind Directions Relative to 500-mb Wind Direction.

Region: Edmonton

Pattern: Scattered - Swath

No. of cases: 34

MBS	161–180	141–160	121–140	101–120	81–100	61–80	41–60	21–40	1–20	0–19	20–39	40–59	60–79	80–99	100–119	120–139	140–159	160–179	CALM	MISSING
	◁COUNTER-CLOCKWISE									— CLOCKWISE ▷										
200					1		2	3	7	8	5	2			1					5
300				1	1		1	5	9	5	6	1		1						4
400			1			1	1	5	12	10	3	1								
500																				
600							1	5	8	17	2	1								
700				1		1	1	1	6	17	4	2						1		
	1		1		1		4	1	6	7	6	6	1							
800				1	1	3	4	2	3	7	4	5	2		1			1		
		1			1	5	1	4	7	3	1	4	2	2		1	1	1		
900				2	3	2	3	2	4	5	2	2		3	1	2	1	2		
			2		6	4	2	1	2	5	1	2		4	3		1	1		

DEVIATION FROM 500-MB WIND (°)

Table 3.7 Frequency Distributions of Surface and Upper-Level Wind Directions Relative to 500-mb Wind Direction.

Region: Calgary

Pattern: Scattered-Swath

No. of cases: 33

MBS	161-180	141-160	121-140	101-120	81-100	61-80	41-60	21-40	1-20	0-19	20-39	40-59	60-79	80-99	100-119	120-139	140-159	160-179	CALM	MISSING
	← COUNTER-CLOCKWISE									CLOCKWISE →										
200						1	3	3	5	3	2		2				1			13
300				2		1	2	3	8	4	2		1	1						9
400					1		1	1	12	12	2	1								3
500																				
600							1	2	12	13	1	1		1						2
700						1	5	4	7	9	1	2	2							2
			1	2	2	1	2	5	4	9	4		1							2
800			3	1	2	1	4	1	1	3	6	1	3	1	3		1			2
	3		2	1	2	2	1	2		2	3	2		4	3	2	1	1		2
900	2	2	2	2	2			3	1		1	3	1	2	2	5	1	1	1	2

DEVIATION FROM 500-MB WIND (°)

Table 3.8 Frequency Distributions of Surface and Upper-Level Wind Directions Relative to 500-mb Wind Direction.

Region: Edmonton
Pattern: Scattered
No. of cases: 37

MBS	← COUNTER-CLOCKWISE ←									→ CLOCKWISE →									CALM	MISSING
	161-180	141-160	121-140	101-120	81-100	61-80	41-60	21-40	1-20	0-19	20-39	40-59	60-79	80-99	100-119	120-139	140-159	160-179		
200		1					1	6	7	9	5			1		1				6
300						2	2	4	12	8		2		1	1					5
400						1	1	3	18	9	1			1				1		2
600			1					2	16	11	2	1	1							3
700				1			2	3	9	9	5	4	2							2
				1	1	3		4	6	6	7	4	1	1						3
800				1	3		1	4	6	5	5	5	2	1	1					3
		1		2		1	2	1	7	3	5	6	3	2	1			1		2
900	2		1	2		1	3		3	4	4	3	6	2	2	1				3
		2	1	2	1	1	2	2	4	3	5	1	2	5	2	1		1		2

DEVIATION FROM 500-MB WIND (°)

Table 3.9 Frequency Distributions of Surface and Upper-Level Wind Directions Relative to 500-mb Wind Direction.

Region: Calgary

Pattern: Scattered

No. of cases: 29

MBS	161–180	141–160	121–140	101–120	81–100	61–80	41–60	21–40	1–20	0–19	20–39	40–59	60–79	80–99	100–119	120–139	140–159	160–179	CALM	MISSING
	← COUNTER-CLOCKWISE									— CLOCKWISE →										
200				1	1	2	2	1	8	3	2	2		1						6
300			1		1	1	2	1	7	7	2	4						1		2
400				1	1		3	1	9	9	2	1						1		1
500																				
600							1	2	10	9	1	2		1	1				1	1
700			1				1	7	8	4	1	1	3	1					1	1
			1		2	1	4	2	4	7	1	2	1	1	1				1	1
800	1	1	3	1	1	3	1	1	2	1	2	3	3	1	2			1	1	1
	1	1		5	1		2	1	1	1	3		5	2	3			1	1	1
900		1	2	1	2	2			2	1	1	5	3	1	2	4		1		1

DEVIATION FROM 500-MB WIND (°)